WEAPONS SYSTEMS FUNDAMENTALS

Basic Weapons Systems Components

PUBLISHED BY DIRECTION OF
THE CHIEF OF THE BUREAU OF NAVAL WEAPONS

NAVWEPS OP 3000 VOLUME 1

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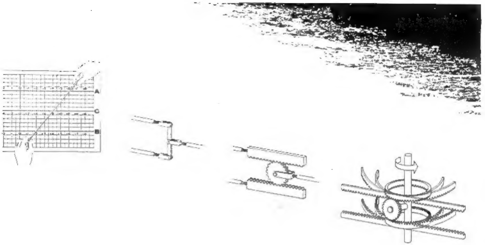


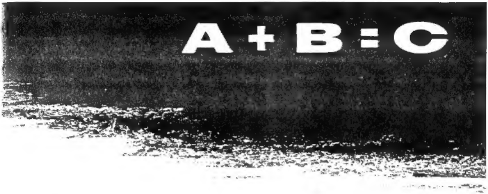
preface

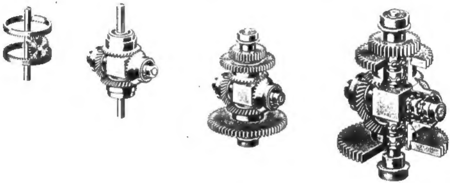
In past years, a broad technical insight into the field of naval weapons could be obtained by making a detailed study of the weapons themselves. The increasing number and complexity of weapons and weapons systems has made it impractical to learn general concepts by such a method.

This publication, therefore, introduces and explains the fundamental principles of weapons and weapons systems in a unique manner. That is, the "hardware" approach and the need to memorize mere facts about specific equipments are abandoned in favor of treating the necessary reasoning processes.

A thorough mastery of the basic principles and concepts presented here will be useful for analyzing and understanding virtually any present-day weapon system. Such knowledge of principles should prove equally effective for approaching most any weapon system problem that may be encountered in the future.

The material presented in this publication has been developed through extensive research regarding both source information and manner of presentation. To conserve the time of the reader, it comprises readily grasped graphic treatments coupled with condensed and closely related text explanations. This arrangement should help not only the student but anyone seeking to refresh his understanding of the subject matter.





In developing this publication, the principles of computing devices have been explained primarily in terms of mechanical rather than electrical analogs. This was done because all analog devices function in accordance with the same basic principles. Mechanical units more clearly illustrate the ideas involved and are more easily understood by the general reader. However, where necessary, important electrical devices are explained in suitable terms.

Every effort has been made to avoid a development based merely on definitions and statements of equations. Rather, the method used is to approach the mathematics by first equipping the reader to understand what lies behind the equations. This insures that the reader will be lead to a "common-sense" viewpoint and a clear physical comprehension upon which the subsequent mathematical treatment can be soundly based.

The material in this publication should prove to be useful as a reference on weapons systems fundamentals for the entire naval establishment, both afloat and ashore — and particularly for those responsible for the operation and maintenance of modern integrated weapons systems.

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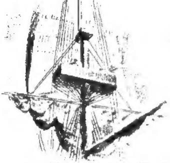


CHAPTER 1

COMPONENTS OF WEAPONS SYSTEMS

- computer
- synchro
- servo
- radar
- sonar
- gyro

INTRODUCTION

In colonial times, control of gun fire was accomplished in a manner similar to that presently used in the control of individual rifle fire. The control of gun fire evolved around the gunner who evaluated conditions and "mentally" computed the gun orders of train and elevation. The accuracy of the gun orders depended not only upon the experience and ability of the gunner, but also on the accuracy of the information supplied to him, or collected by him. Several men were usually involved in the operation of a weapons system to assist the gunner in securing needed information, and in positioning the gun.

WINDAGE

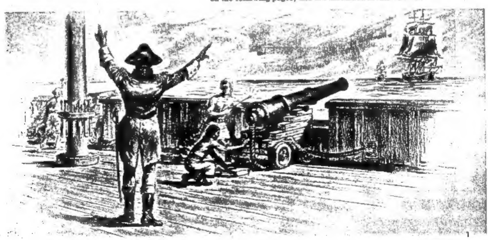
GRAVITY

TARGET SPEED

Collecting and evaluating this information, and also the manual positioning of the gun in response to the gun orders, required a long time. Combined inaccuracies, caused by human fallibility and inaccuracies due to poor workmanship on the gun, resulted in limited range in the accuracy of gun fire.

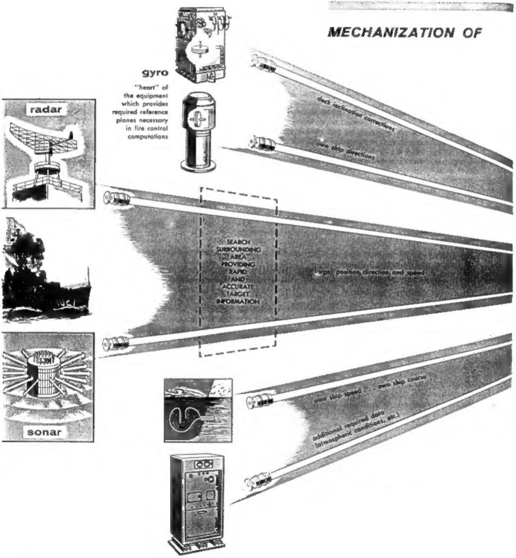
As gun construction improved due to continued development (rifling, closer tolerances, etc.), the accuracy and effectiveness of gun fire became more dependent upon the fire control operation. Increased speed and fire power of the enemy accentuated the need for faster fire control having a higher degree of accuracy.

Improved fire control was achieved through mechanization of as many manual operations as possible. Components which enabled the mechanization of important fire control operations are shown on the following pages, and are discussed in this volume.

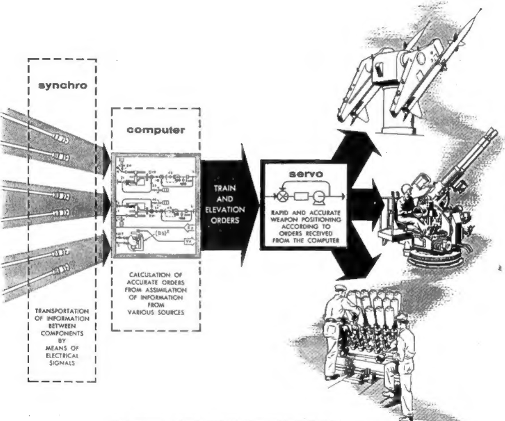


COMPONENTS OF WEAPONS SYSTEMS....

MECHANIZATION OF



FIRE CONTROL OPERATIONS



The components shown above are discussed in detail in volume 1. Application of these and additional components in the weapon fire control problem will be seen in volumes 2 and 3. (The general term "weapon fire control", is used interchangeably with the shorter expressions "fire control" or "weapon control". To indicate specific applications to certain weapons, terms such as "gun fire control" or "missile fire control" are used.)

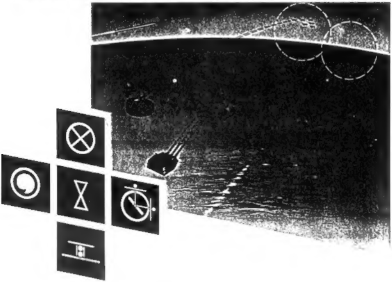
CHAPTER 2

Introduction to BASIC MECHANISMS OF COMPUTERS

The basic purpose of fire control is to direct rapid, continuous and accurate fire at enemy targets. When a land, sea or air target is fired upon, variable factors affect the chance of scoring a hit. Among these are target size, speed, direction, altitude and range; weapon range, projectile velocity and trajectory; wind velocity and direction; own ship speed, pitch and roll and course, and other controlling conditions.

Before the advent of modern warfare the gunner would estimate the values of these factors, and, with experience, he stood a fair chance of hitting a relatively slow moving target at close range. It was learned that by using precise scientific means, most of the important factors could be measured and calculated. Using such data, targets at further distances and higher speeds could be hit by gunners who have had less experience. The computations required in fire control are complex and lengthy. If done by hand, by the time that target position and speed had been measured and corrected, the target would no longer be at that position. It became necessary to calculate more rapidly and with a higher degree of accuracy than possible for human beings.

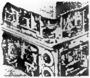
For this purpose, computers were developed. They solve equations and perform arithmetic, calculus and trigonometric operations. Also, they store information for future use. Computers can be mechanical or electronic. Most ships use mechanical computers because, although they may be less accurate they are more rugged, less costly, and take up less space than electronic computers.



scope of section

Mechanical computers are relatively simple, considering the many varied operations they perform. Each computer is a combination of a few simple basic mechanisms. There is a mechanism for adding and subtracting, one for multiplying and dividing, one for finding sines and cosines, etc. These mechanisms may be connected in various ways.

Shown to the right is a cut-away view of a computer. By studying the computer in a systematic way we can gain an idea of its overall operation.



COMPUTER SYSTEMS

SOLUTION OF EQUATIONS

consider a typical problem

The "black box" which converts the input to the output is usually symbolized according to its function. For instance, all multipliers are signified by one symbol:

⌛ means multiplier

Each integrator, trigonometric device, and addition and subtraction device has its symbol. For the present, however, we will use just a black box to represent the mechanism. Later we will substitute symbols for the boxes. Inputs and outputs will be indicated by directional arrows.

Consider the target as an enemy plane. The formula for Rv2 or predicted height of the target at point of contact with the projectile is:

Rv2 = R sin E + T2 x Mv

where R = present range
E = present elevation
T2 = time of flight of projectile
Mv = rate at which height of target is changing.

these are the INPUTS to the computer.

we want

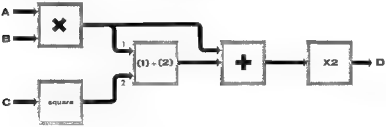
Rv2 AS AN OUTPUT

Four separate operations are involved

1 Find sin E
2 Multiply sin E by R
3 Multiply T2 by Mv
4 Add R sin E to T2 Mv

ANALYSIS OF COMPUTER MECHANISMS

By studying the interior of a computer, we can discover the operation it performs and the equation it represents. This can be done quite easily in a step-by-step process. How do we analyze the following computer mechanism?

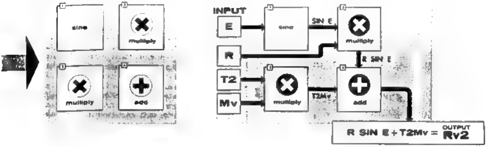


Note In certain cases the equations arrived at by mathematical analysis of the problem are extremely complicated. The size of equipment necessary to solve them is often impractical. Often they can be replaced by an empirical equation, arrived at through experiment, without a significant decrease in accuracy. This use of less accurate, but simpler, equipment is desirable as long as accuracy is still kept within allowable limits.

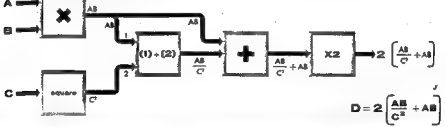
HOW COMPUTERS ARE CONSTRUCTED

For each of the four operations we need a basic mechanism.

We add the inputs, and connect the mechanisms.



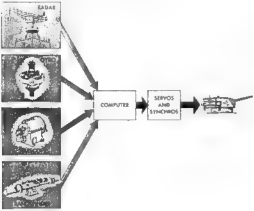
The first step in finding the equation represented by the computer ■ to label each line connecting the boxes (shafts connecting the mechanisms) with the values they carry. Start from the left, and move to the right. The numbers (1) and (2) serve merely to indicate which of the inputs is the numerator and which is the denominator in the dividing mechanisms. Here is the computer with all connecting shafts labeled. This procedure can be applied to even the most complicated computing mechanisms in a similar way.



SUMMARY

In the following sections we will deal with a number of mechanical devices to perform operations such as described above. We do not cover all of them, but by understanding those we explain, and knowing how they are used, we can apply these principles to any computing system encountered in the future. The chapter will concentrate on devices used in naval computers. They are mostly mechanical, but both electrical and electro-mechanical devices are used.

Computers alone cannot determine correct positions of guns. Information must be obtained and handled by such devices as radar, sonar, gyroscopes, synchros, servos and rangefinders. "Basic Mechanisms" will be devoted solely to the elements of a computer, but it must be realized that computers depend upon other devices for information and transmission of values.



BASIC MECHANISMS

computer inputs

The computer receives information such as "yards of range" or "degrees of elevation" and "knots of ship speed". Most of these quantities are constantly changing. At every instant, however, each of these quantities has a definite numerical value. These values are used to position the mechanisms in the computer. The shafts on computers represent these values. On some shafts, one revolution represents 3° of elevation; on other shafts, one revolution represents 100 yards of range. Then, in the first case, one half a revolution represents 1.5° of elevation, or, in the second case, 50 yards of range. The amount of rotation of the shaft represents a definite value in which we are interested.

NOTE
It is possible to have computing mechanisms which involve no more than the motion of a stick or a piece of graph paper. Such mechanisms, although simple, are difficult to attach to other mechanisms to form computing systems. Most practical computing mechanisms, therefore, have shaft rotations as inputs and outputs.

a simple basic mechanism

Each mathematical operation is replaced by a mechanism. Most of these mechanisms are fairly simple. With a good understanding of these basic mechanisms it will be easy to see how they can be combined in a computer. The following chapters will be devoted to explaining these mechanisms.

In fire control the usual procedure is to put into a computer those quantities which effect the chance of hitting the target, and get out of the computer the correct aiming of the guns. This must be done continuously, rapidly and accurately as conditions change.

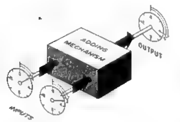
Suppose we had an input of A, and we wanted an output of 2A.

Let us take input A, and represent it as a turning shaft.

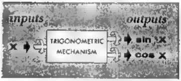
Then output 2A will be a shaft rotating twice as much as input A.

and outputs

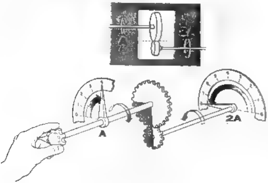
Ignoring the insides of the mechanism, let us consider it just as a "black box". As an input to the black box, let us consider that we have two shafts. One is turned until it has a value of 3, and the other is turned until it has a value of 2. We have another shaft as our output. If the mechanism performs the function of adding, then the output shaft will have a value of 5. No matter what values are put on the input shafts, the output shaft will give their sum.



The number of inputs and outputs can vary. A trigonometric mechanism can have a single input and two outputs. The input shaft has a value of X, and the output shafts have values of sin X and cos X.



A pair of gears having a ratio of 2:1 will do this



The gear train is one of the "basic mechanisms" from which computers are designed and constructed.

If we turn the knob to give us a reading of 4 on the input scale we will get a reading of 8 on the output scale because the output gear revolves twice as much as the input gear. No matter what value we set on the input scale, we will always get twice that value on the output scale. The device shown is an important computing mechanism. By means of this device, consisting of a pair of gears in the black box, we performed a continuous and accurate operation.

The values are represented by revolutions of the two shafts. In the present case, we want to read the values. To do this we use two dials. However, we may not always be interested in the individual values. The output of one mechanism is often used as an input to another mechanism. In such cases, the dials could be eliminated.

PROBLEMS

1. Design a mechanism to perform the operation

   a. 3A

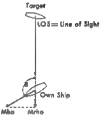
   b. 2.5A

   c. $\frac{1}{2}$ A

2. The velocity of a ship in the direction of the line of sight (Mrho) is an important quantity in fire control. When the velocity in the direction of motion (Mho) is known, this value is found by means of a component solver. However, it can also be found by means of equation:

   Mrho = Mho Cos B

   where B is the angle between the line of sight and the direction of motion. Design a system to solve this equation using the method outlined on the previous page. Mho and B are inputs; Mrho is the desired output.



3. Design a system to solve the following equations:

   The inputs are B, C, and D
   The output is A

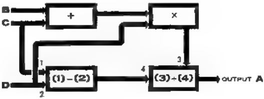
   a. $A = \dfrac{2C - \sin B}{D}$

   b. $A = \dfrac{C - 2\sin B}{D}$

   c. $A = \dfrac{C^2 - B^2}{\sin D}$

   d. $A = \dfrac{(C + B)\,D}{D - C}$

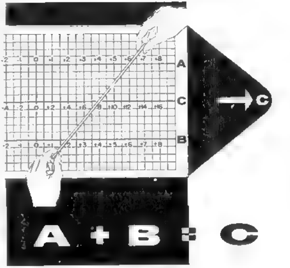
4. Determine the equation solved by the following mechanism.



SECTION 1

ADDITION AND SUBTRACTION DEVICES

As pointed out in the introduction in this chapter, a simple rod and a piece of graph paper can be used to fashion simplified computing devices. These simplified devices operate on the same principles as actual computing mechanisms used in Naval weapons systems. The rod and graph paper can be used to demonstrate mechanical addition and subtraction in a very straightforward manner. On the graph paper draw two parallel lines A and B any distance apart and mark off the lines at uniform intervals either side of zero. Values to the right of zero are taken as positive, and those to the left are taken as negative. Draw a third line C midway between lines A and B, and mark it off at uniform intervals half as large as those on scales A and B. Now assume it is desired to find the sum of 6 and 2. Place the rod on the graph so that it crosses the A scale at +6 and the B scale at +2. The rod will then cross the C scale at the +8 graduation which is the required sum. Using this same method, any two numbers within the range of the scales can be added. It is suggested that the reader actually try various sums right on the graph in the illustration. The edge of a ruler or piece of paper can be used as a substitute for the rod. In addition to summing positive quantities, try various combinations of positive and negative values.

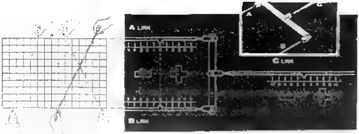


The principle illustrated above is inherent in the operation of all mechanical addition and subtraction devices used in Naval computers. Such devices are called "differentials". Basic mechanisms classed as differentials can take a number of forms depending on the details of the design selected. To meet the requirements of modern weapon systems, differentials must be capable of producing accurate and instantaneous sums or differences from inputs that are rapidly and continuously changing. The design must be such that the mechanism is simple, rugged, and reliable to avoid breakdown in service. Generally speaking, accuracy is the prime consideration in devices employed for weapon systems computations. The physical movement which represents a mathematical quantity must be accurate within extremely close tolerances over the entire range of the quantity. For this reason, although the mechanisms are simple in principle, they must incorporate design features that insure precision performance even under adverse conditions, thus complicating their construction.

scope of section

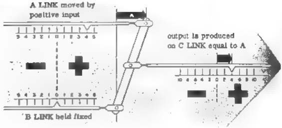
In the following pages, mechanical differentials are explained in detail. The principles of their operation are developed in step-by-step fashion to show the basic principles which underly the construction of all types. The limitations inherent in each type of differential are illustrated and analyzed, and the means used for getting around the limitations are discussed. The subject of differentials is ended by showing their practical applications in solving actual equations that are encountered in weapons systems. An explanation is also given of how differentials perform an important function by acting as error detectors in precision servo loop systems.

LINKAGE



The simple graphical device can be reproduced mechanically by a free lever supported by three links. The output and two input quantities are represented as linear link displacements that can be observed by the use of scales.

HOW the linkage WORKS

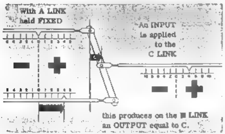


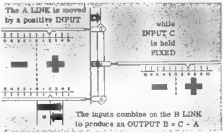
Note

Since the C link is connected halfway between the A and B links, the actual output motion is only one half the input motion. However, since a 2:1 scale is used, the output reading is equal to the input applied.

input-output variations

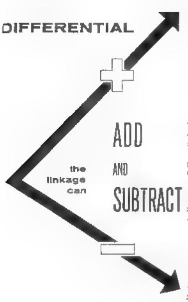
The input-output arrangement is not limited to the one shown at the top of the page. Actually, the output can be taken off any one of the three links, and the remaining two can be used for applying the inputs. Whatever the arrangement, the basic equation defining the relationship of the three quantities remains exactly the same, that is to say: C = A + B. For example, if C and A are used as inputs, the value of the output is determined by solving the equation above for B, that is: B = C - A.

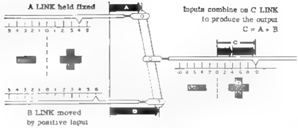




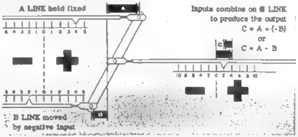
The positioning of the lever accomplishes the addition or subtraction. Whether the links push or pull the lever is unimportant. The links are merely methods of applying inputs to the lever. Thus, the links can be put on either side of the lever without affecting the differential action. A few equivalent arrangements are shown.

DIFFERENTIAL



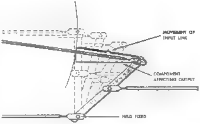


The only difference between addition and subtraction results from the direction of the quantities involved. The process of subtraction is shown as the addition of a negative quantity. This is accomplished by moving the link negatively. Subtraction can also be considered as the subtraction of a positive quantity. This would be accomplished by reversing the signs of the scale and moving the link positively.



operating limits

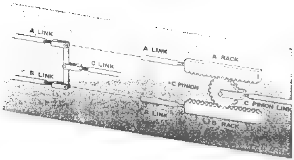
In a linkage differential, the angular movements of the lever tend to cause changes in the direction of the input links as shown to the right. This may cause errors since only a component of the input link movement affects the output reading. In practice, this type of error is minimized by restricting the difference between the inputs to relatively small values, or by arranging the input mechanism so that changes in direction are kept small. Note that in any case the difference in the inputs can not be any greater than is allowed by the lever length as measured between the centers of the input link pins.



summary

By differential action, we mean the combining of two input quantities in such a way as to produce an output that is proportional to their sum or difference, depending upon the relative directions in which the inputs are applied. The linkage differential represents only one way of obtaining differential action. In the following pages, we will further develop the principles of differential action and show their application in other devices used in ordnance equipment.

RACK and PINION DIFFERENTIAL

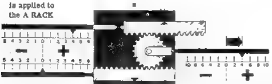


Another type of adding and subtracting mechanism, similar in many ways to the linkage differential, is the rack and pinion differential. Here, the essential parts of both types are shown for comparison. The function of the lever and C link is now performed by the C pinion and the link attached to its shaft. The function of the A and B links is accomplished by the A and B racks riding on the periphery of the C pinion so that they always remain parallel. With this arrangement, the output remains accurate regardless of the size of the inputs. Note that the difference between the inputs can not be any greater than is allowed by the combined length dimensions of both racks. As was the case in the linkage differential, the output and two input quantities are represented as linear displacements that can be observed by means of scales. Again, any of the three movements in the mechanism can be used as the output while the other two movements are used for input quantities.

HOW the rack and pinion differential WORKS

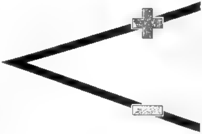
Here the rack and pinion differential is shown with scales for the inputs and output. The explanation covers how the differential adds and subtracts when the output is taken off the C pinion link.

An INPUT is applied to the A RACK



while the B RACK is held FIXED

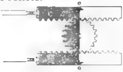
This produces on the C PINION LINK an OUTPUT equal to A



ACTION of racks and pinion

Since the entire functioning of the device depends on the rolling action between the pinion gear and the racks, this action will be explained before considering how the mechanism adds and subtracts. For simplicity, the C pinion link has been omitted from the two illustrations at the right.

STARTING from the ZERO POSITION



Assume that a movement of 6 TEETH is applied to the A RACK

while the B RACK is held FIXED

The 6-TOOTH movement produces a rolling action between the C pinion and racks of:

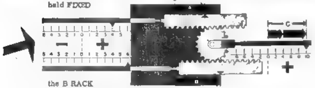
3 TEETH here
and
3 TEETH here

Thus, the C PINION is displaced through a LINEAR DISTANCE equivalent to 3 TEETH; that is, ONE-HALF the linear movement of the A rack.

The halving action shown above is the same as that inherent in the linkage differential. Therefore, a 2:1 scale should be used for observing the linear values represented by the pinion shaft displacement.

The inputs combine on the C PINION LINK to produce an OUTPUT C = A + B

With INPUT A held FIXED

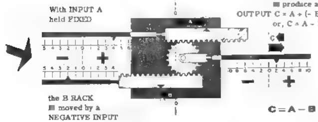


the B RACK is moved by a POSITIVE INPUT

C = A + B

The inputs combine on the C PINION LINK to produce an OUTPUT C = A + (- B) or, C = A - B

With INPUT A held FIXED



the B RACK is moved by a NEGATIVE INPUT

C = A - B

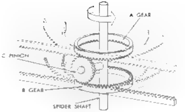
summary

In practical applications of the rack and pinion differential, problems may arise because there is a space limitation. Since the pinion can not be permitted to roll off either rack, the allowable difference between the two inputs is restricted by the length of the racks. In addition, since the output and inputs are linear displacements, large values tend to increase the length of the mechanism to an impractical degree. The following pages show a differential device that overcomes these space restrictions effectively.

GEAR DIFFERENTIAL

how restrictions are avoided

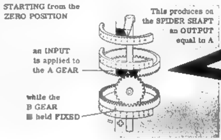
Here is a simple way to avoid restrictions on the output and input values that occur with the rack and pinion. Make the racks endless by rolling them up and joining their ends so that they form two face gears (A gear and B gear). Also attach the pinion axle to a spider shaft. The pinion now rolls between the gears in the same way that it rolled between the racks. The only real difference ■ that the output and inputs formerly represented by linear motions are now represented by angular rotations. This change was accomplished without any effect on the differential action. The spider output is even subject to the same halving action as the pinion shaft had before.



how the gear differential works

This ■ how the gear differential adds and subtracts when the output ■ taken off the spider shaft.

Three SCALES are shown on the mechanism so that the output and input rotations can be observed. The scales remain fixed while the gears rotate. Note that a 2:1 scale ■ used on the spider to account for differential halving action.



A PRACTICAL TYPE OF

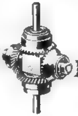
The mechanism described above is highly simplified to show only the essential operating parts and ■ not constructed for actual use. Following ■ a practical differential widely used in ordnance.

note *Ball bearings are used to support all rotating parts.*

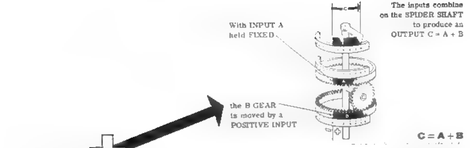
the bevel gear differential

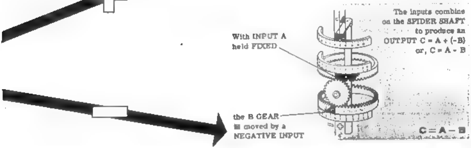
To convert this simplified device into a practical bevel gear type. . .

. . . the C pinion and the A and B gears are changed to bevel gears. Another bevel gear ■ mounted on the spider to provide balanced loading and ■ minimize backlash. The spider shaft is changed to a rugged assembly of two shafts and a block. In this type of mechanism, the A and B gears are called end gears, and the gears performing the function of the C pinion are called spider gears.

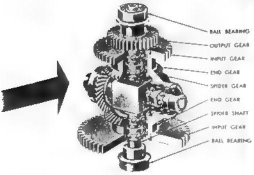


Spur gears are attached to the spider and end gears to provide exterior input and output connections.



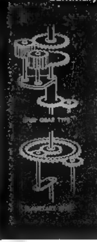


GEAR DIFFERENTIAL



Shown above is the internal construction of a typical bevel gear differential. Parts are named assuming the spider is the output.

summary

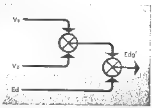


Another form of the gear differential is the spur gear type. The essential operating principle is exactly the same as for the bevel gear differential. The main difference is simply that all the gears used in the assembly are spur gears. There are still other forms of mechanical differentials (such as planetary types). In ordnance equipment, the idea of differential action is used in many clever ways, and even may be built into a mechanism in such a manner that the action is not at all clear without detailed study. However, in all cases, the use of the principles developed in this lesson will assist in analyzing the action of any differential device that may be encountered.

APPLICATIONS . . . how differentials are used

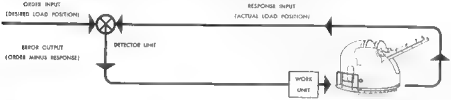
computation

Basically, all of the differential devices we have studied are simply adding machines that can continuously produce difference or sum values from two inputs that may themselves be changing quite rapidly. In fire control, the gun elevation required to hit a moving target is obtained by combining three values: the director elevation Ed, sight angle Vs, and a correction for the tilting of the gun trunnions Vz. Gun elevation is obtained by solving the equation Edg' = Vs - Vz + Ed. This equation can be instantly and continuously solved, as the inputs change, by two differentials as shown in the schematic diagram at the right.



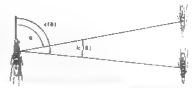
comparator action

Two quantities can be compared easily to make sure they are equal. This can be done with a mechanical differential by applying the quantities as inputs in such a way that one [redacted] subtracted from the other. Now, the size of the output equals their difference and [redacted] direction indicates which of the two values is the larger. When the output [redacted] zero, the values are equal. In this application the differential is called a comparator or detector unit. Below [redacted] an elementary servo loop mechanism in which the load position is controlled by a weak order input. The order input and a response input (which represents the position of the load) are used to a differential used as a detector unit. Any difference between order and response produces an error output which causes the work unit [redacted] drive the load until the error is cancelled. When response and order are equal, the error [redacted] zero and the work unit stops.

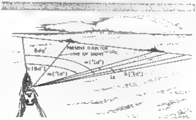


PROBLEMS

1. When a target is tracked, the bearing at any instant c(B) [redacted] equal to the initial bearing [redacted] plus the change in bearing ic(B) generated during the tracking time. That is, c(B) = [redacted] + ic(B). Work out the details of an actual computer using a differential that can solve this equation. Be sure to include properly graduated scales. Consider how inputs can be applied and how parts can be mounted.



2. When a target is fired on, gun train order Bdg' is obtained by offsetting the gun from the present director line of sight. Gun train order is the sum of director train c(Bd') and the following offset angles: m('Ld') to account for target movement during projectile flight, w('Ld') to account for wind effect, b('Ld') to allow for the curvature of the projectile flight path, and Lz to correct for tilting of the gun trunnions. Examine the figure and write the equation for Bdg'. Make a schematic diagram showing how the equation can be mechanized by a combination of differentials.

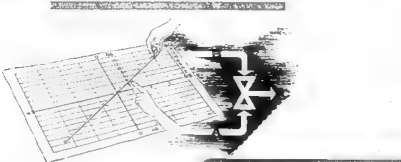


2

MULTIPLICATION AND DIVISION DEVICES

Multiplication and division mechanisms used in computers operate on a geometric principle similar to that described in the preceding section on differentials. Again, the basic principle can be demonstrated by setting up a simple device consisting of a rod and a piece of graph paper. Scales are marked on the graph paper as shown in the figure, the A scale being one unit to the right of the vertical axis. A pivot is used so that the rod can be rotated about the origin and a sliding wire clip is placed on the rod to act as an indicator or multiplier pin. This forms an elementary multiplier.

To use this multiplier, proceed as follows: (Assume that we wish to multiply 4 by 3.) First swing the rod until it crosses the A scale at the +4 graduation. Holding the rod in this position, slide the multiplier pin along the rod until it is directly above the +3 graduation of the B scale. Reading across horizontally to the right of the multiplier pin, obtain the answer +12 from the C scale. This particular computation is shown in the figure. Within the ranges of the scales, any values of A and B can be multiplied to produce product C, thus solving the equation $C = A \times B$.



geometry of the multiplier

The lines formed by the rod, the distance B along the horizontal axis, and the vertical distances A and C make up two superimposed right triangles, one having legs equal to A and to 1, and the other having legs equal to C and to B. Since legs A and C are parallel, the two triangles are similar. Therefore, the following proportion can be written: $\frac{A}{1} = \frac{C}{B}$

Cross multiplying gives the basic multiplier equation: $C = A \times B$

NOTE:

Here, the A scale is placed at a horizontal distance of one unit from the origin to simplify the proportion. Actually, the distance of the A scale from the origin can be any constant value K, giving the generalized proportion $\frac{A}{K} = \frac{C}{B}$. Cross multiplying gives $KC = AB$. The constant factor K in the product can be accounted for easily in the calibration of the C scale.

SCOPE OF SECTION

In the following pages, the basic geometry of the multiplier is developed in detail to explain division as well as multiplication and to show how positive and negative values are handled. Then, on the basis of this geometry, a description is given of how actual multiplier mechanisms are built to produce the required movements and to establish the necessary relationships between the inputs and the output.

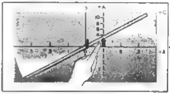
The section is concluded by a discussion of applications of multiplier mechanisms in Naval weapons systems and by problems chosen to bring out the principles covered.

OPERATING PRINCIPLES OF MULTIPLIERS

The elementary graphical device described on the preceding page establishes, by means of the similar right triangles, a definite mathematical relationship among the three variable quantities A, B, and C; that is, C = AB. The device works in such a way that if any two of the variables are set in, the geometric action automatically solves the equation to produce the third variable. The various possible solutions are:

$A = \frac{C}{B}$ $\qquad B = \frac{C}{A}$ $\qquad C = AB$

Accordingly, when solving for C, the device acts as a multiplier. When solving for A or B, it acts as a divider. At the right, the action of the device is shown in detail for both multiplication and division.

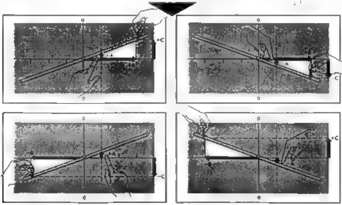


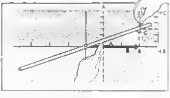
ASSUME AN INPUT A IS APPLIED by rotating the rod until it crosses the A axis at the selected reading.

operation with positive and negative values

The mathematical and geometric relation described by the equation above holds true for negative as well as positive values of the variables. As usual, negative values are applied in the direction opposite to that used for positive values.

Shown below is the pattern of signs as they occur in the graphical device. Note that this pattern follows the standard mathematical convention for signs; that is two positive or two negative inputs produce a positive output and a positive and a negative input combine to produce a negative output.





C = A x B

After input A is applied, either B or C may be selected as the other input.

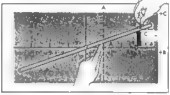
If B is applied, the output C is the product of the inputs, A x B.

Input B is set by sliding the multiplier pin until it is vertically above the selected value of B as read on the B scale. Output C is read from the C scale.

If C is applied, the output B is the quotient of the inputs, C ÷ A.

Input C is set by sliding the multiplier pin until it is horizontally opposite the selected value of C as read from the C scale. Output B is read from the B scale.

The choice of the inputs and outputs depends only on the computer design requirements.

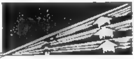


B = C ÷ A

multiplier input-output movements

From the preceding explanation, it can be seen that from the mechanical viewpoint there are but three movements involved in the graphical multiplying device.

1. A rotation of the rod about the pivot at the origin. This angle of rotation is determined by the value of A measured vertically along the A-axis.



2. A movement of the multiplier pin measured horizontally along the B-axis.

3. A movement of the multiplier pin measured vertically along the C-axis.

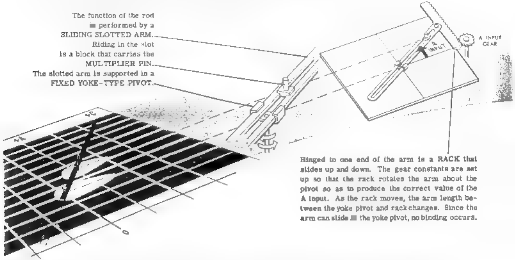
Regardless of the mechanical details, any actual multiplier mechanism based on this principle must produce these three simple movements. This fact is a powerful aid in understanding and analyzing such mechanisms.

SUMMARY

In the remainder of this section, the operating principles of multiplication and division devices are applied in explaining the construction of mechanical multipliers used in Naval weapons systems. Various ways for producing each of the required motions are shown and are then used to develop typical complete multiplier mechanisms in a step-by-step fashion. Where limitations exist in the mechanisms, they will be pointed out and explained.

the construction of an actual multiplier

is arranged to produce the same movements as those in the basic graphical multiplying device. Each movement is accomplished by an individual mechanism. These mechanisms, in combination, form the complete multiplier. There are many types of multipliers, depending on the particular mechanisms used. Developed below is a multiplier known as the rack-type.



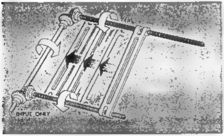
The function of the rod is performed by a SLIDING SLOTTED ARM. Riding in the slot is a block that carries the MULTIPLIER PIN. The slotted arm is supported in a FIXED YOKE-TYPE PIVOT.

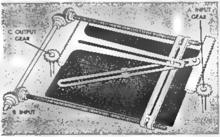
Hinged to one end of the arm is a RACK that slides up and down. The gear constants are set up so that the rack rotates the arm about the pivot so as to produce the correct value of the A input. As the rack moves, the arm length between the yoke pivot and rack changes. Since the arm can slide in the yoke pivot, no binding occurs.

screw-type multiplier

Here is one type of mechanism that can be used in place of a slotted rack. It consists of a slotted slide with threaded holes at each end to receive two lead screws. The screws are geared together through the input shaft so that the input rotation drives the slide back and forth evenly.

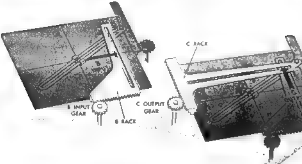
The lead screw and slide mechanism is used in conjunction with rack mechanisms to form a device known as a screw-type multiplier. This multiplier is essentially the same as the rack-type shown above except that the screw and slide arrangement is used in place of the slotted rack for the B input.



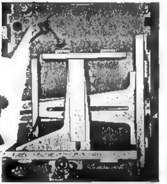


note *The screw mechanism is irreversible. That is, the multiplier pin can not drive the slide along the screws. Therefore, this mechanism can only be used for an input.*

The multiplier pin extends up through a slot in the arm of a second sliding RACK. This rack positions the multiplier pin so as to produce the value of the [redacted] input.



At right angles [redacted] the B rack is a third RACK having a slot that also engages the multiplier pin. As the pin is moved by the A and B inputs, it positions this rack to produce the [redacted] output.

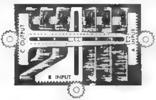


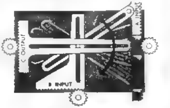
The three component mechanisms developed at the left form the complete rack-type multiplier. Shown above [redacted] an actual rack type multiplier used in a Naval computer. This mechanism has a slightly different arrangement of the racks. [redacted] all rack-type multipliers any two of the racks can serve as inputs and the other as the output. Thus, the device can function equally well as a divider and as a multiplier.

zero position When one of the multiplier inputs [redacted] at zero, the output must remain at zero regardless of the value of the other input quantity.

The A input [redacted] at zero when the slot in the A arm [redacted] lined up with the slot in the C rack. In this condition, as shown below, any movement of the B rack merely causes the multiplier pin to slide along the lined up slots. Therefore the multiplier pin does not move vertically and there is no output motion of the [redacted] rack.

The B input [redacted] at zero when the multiplier pin is directly over the yoke pivot as shown below. Now, since the multiplier pin is at the pivot axis, any A input causes the A arm to rotate about the multiplier pin. Accordingly, there is no linear displacement of the pin and hence, no output on the C rack.





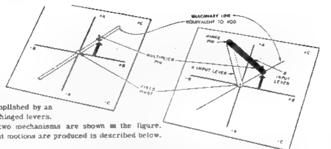
note *The zero positions of the multiplier are useful for checking and adjusting the mechanism and for insuring that it is operating correctly.*

Summary

The mechanisms of the screw-type and rack-type multipliers are essentially devices for providing the three basic movements related to the setting up of two similar triangles. Various multipliers of these types are encountered in computers, ... differ in detail as regards location of the pivot and the arrangement and shape of the racks. However, all work on the principle just explained.

Next we will take up another multiplier that provides the same three basic movements but uses a different type of mechanism.

LINKAGE MULTIPLIERS



The same movements that are produced by the elementary graphical multiplier can be accomplished by an equivalent device consisting of two hinged levers. The corresponding parts of the two mechanisms are shown in the figure. The manner in which the equivalent motions are produced is described below.

equivalence of mechanism motions:

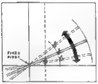


FIGURE 1

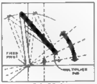


FIGURE 2

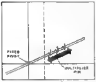


FIGURE 3

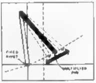
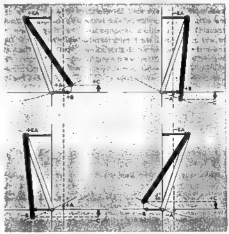


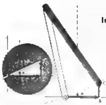
FIGURE 4

Effectively, the rod in figure 1, merely sets up a straight line between the fixed pivot and the multiplier pin. This straight line is rotated to produce the A input by physically swinging the rod about the fixed pivot. The lever mechanism in figure 2 establishes a straight line (the imaginary line) between the fixed pivot and multiplier pin that is exactly equivalent to the straight line set up by the rod. The imaginary line is rotated to produce the A input by physically swinging the entire lever mechanism about the fixed pivot. The motion of the multiplier pin along the rod as shown in figure 3 is accomplished in the lever mechanism by holding the A input lever fixed at the position for any given A input, and then swinging the B input lever about the hinge pin as shown in figure 4. Of course, the multiplier pin moves in an arc about the hinge pin, rather than in a straight line. However, with long levers and small angular openings, the difference between the arc and the straight line is negligible. It can be seen from the above analysis that the motions produced by the rod and pin mechanism can be closely reproduced by the hinged lever mechanism.

positive and negative values

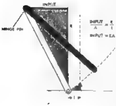
The lever mechanism handles positive and negative values in the same way as any other multiplier using the similar triangle principle. For each movement, one direction is selected as being positive; the opposite direction is then negative. The directions are established so that the pattern of the signs follows the laws for multiplication. This pattern is shown in the diagrams at the right. (Only the A and B input levers are illustrated.) Note that in the pattern of signs, two positive or two negative inputs produce a positive output, and a positive and a negative input combine to produce a negative output. In the arrangement shown, A is positive when the A input lever is tilted to the left and negative when it is tilted to the right. B is positive with the B input lever swung to the right of the A input lever and negative when it is swung to the left of the A input lever. C is positive when the multiplier pin is above the horizontal axis through the pivot and negative when the multiplier pin is below the axis.





lever multiplier geometry

The diagram to the left shows that the geometry established by the lever mechanism is the same as the geometry established by the rod and pin mechanism. Therefore, the lever mechanism solves the basic equation C = A x B.

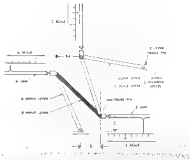


It is convenient to rotate the lever mechanism by applying an input [redacted] the hinge pin. The distance by which the hinge pin must be moved [redacted] directly related to the value of A, as may be seen by analyzing the diagram at the left. Since their legs are mutually perpendicular, the two shaded right triangles are similar. By the proportion shown, the input [redacted] equal [redacted] KA. For small rotation angles, the value of [redacted] remains nearly constant. This constant factor [redacted] accounted for in the scale for the A input.

note

In the lever mechanism, any two of the values can be used as inputs and the third as the output. The mechanism can therefore function either as a multiplier or as a divider.

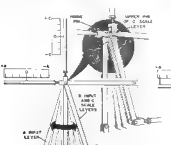
external link connections



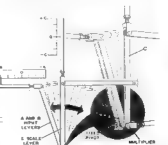
External connections to the A and [redacted] input levers are made by means of links to form a complete linkage multiplier. The movements of the links are restricted to relatively small input values to insure accurate operation of the mechanism. The A input link is attached to the hinge pin and the [redacted] input link is attached to the multiplier pin. The vertical movement of the multiplier pin represents the C output. Since the multiplier pin can have a considerable horizontal movement due to the B input lever motion, an additional pair of levers is usually used to transfer the C output value to the C scale. (These transfer levers have no computing function.)

zero position

When A [redacted] zero, the hinge pin is directly under the upper pin of the C scale lever, and the [redacted] scale lever and B input lever are superimposed. When [redacted] is varied, the two superimposed levers swing together about the hinge pin axis and therefore there [redacted] no [redacted] output.



With [redacted] zero, the multiplier pin is directly over the fixed pivot. The B input lever and A input lever are superimposed. When the A input [redacted] varied, the two superimposed levers swing together about the fixed pivot and again there is no C output.



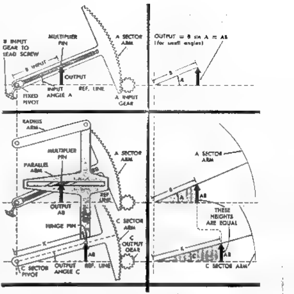
summary

Although there are certain geometrical approximations in the linkage multiplier, the device has the advantage of comparative simplicity of construction. However, if the movements are kept within proper limits, the linkage is sufficiently accurate for precision computation. Next we will consider another multiplier incorporating similar approximations and will take up some other considerations relating to multiplication in computers used in weapons systems.

SECTOR MULTIPLIERS

Some multipliers operate on a geometric principle slightly different from that previously described. The computing portion of one such multiplier is shown to the right. It consists of a pivoted sector arm along which a multiplier pin can be moved by a lead screw. The A input is applied as the angle between the sector arm and the reference line, and the B input as the distance between the pivot and the multiplier pin carried on lead screw. The output is taken as the vertical height of the multiplier pin above the reference line. The input and output quantities form the right triangle shown next to the sector arm. Solving the right triangle gives: Output = B sin A. However, for small angles up to about 1/3 radian (20 degrees), the sine is nearly equal to the angle in radians. Hence, the equation for the output can be rewritten as Output = AB. This means that within its range the mechanism acts as a multiplier (to a close approximation).

The additional mechanism shown to the right in heavy line is provided merely to pick off the linear output of the A sector arm and convert it to an angular quantity. The mechanism is set up so that the radius arm, parallel arm, and C sector arm form a parallelogram with the result that the slot in the parallel arm always remains parallel to the reference line. The multiplier pin of the A sector arm projects up through the slot and moves the parallel arm an amount equal to output AB. This linear output is applied to the C sector arm causing the arm to rotate through output angle C. As shown in the diagram, linear motion AB, angle C, and the constant K(distance between C sector pivot and hinge pin) form a right triangle. Solving the triangle gives: K sin C = AB. Again, for small angles sin C is almost equal to C.



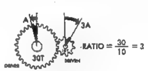
Hence, the equation can be rewritten as KC = AB. The constant K is accounted for in the external gearing. The complete sector multiplier in the form shown here is actually used in computers.

MULTIPLYING BY A CONSTANT

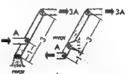
Any of the complete multipliers that have been described can be used to multiply a variable by a constant as well as to multiply two variables. However, for multiplying by a constant, the use of such complex devices is uneconomical in both cost and space utilization. There are many simpler and more compact devices available for the handling of constant factors. All of these devices are based on a fixed ratio between the variable input and the output. A number of different types of simple constant multipliers are shown at the right. These and many other similar devices are employed extensively throughout Naval computers.

scale factor The simplest way to multiply by a constant is to introduce the ratio into the scale or dial from which the value of the product is read.

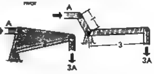
gears A pair of gears is a device that can be used as a constant multiplier. The constant is the ratio of the number of teeth on the driving gear to the number of teeth on the driven gear.



levers When pivoted levers are used, the constant factor is established by the ratio of the arm lengths as measured from the fixed pivot. Two examples of levers are shown.



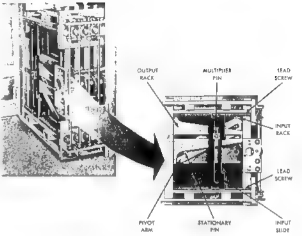
bell cranks These cranks are essentially the same as levers. They allow the input and output to move in different directions. The bell crank can have any desired angle and shape.



actual multiplier applications

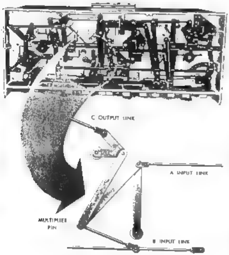
screw-type multiplier

Here is a bank of four screw-type multipliers as actually installed in a Naval fire control computer. (To expose the bank, some of the surrounding mechanism has been removed.) The details of one multiplier of the bank is shown at the far right. Compare this photograph with the schematic representations previously given for the screw-type multiplier.



linkage multiplier

The photograph here shows the internal mechanism of a linkage type ballistics computer for a fire control system. The inset is an enlarged view of one of the multiplier linkages. Note that in this case, a bell crank is used to transmit the output to the remainder of the computing system. Also observe how the lower input (to the multiplier pin) is applied through a connecting link. This illustration shows only one of the many input-output arrangements that can be used. Even the form of the multiplier linkage itself can be varied to meet the physical design requirements of the computer as regards range of operation and available space.



summary

The foregoing covers the principal types of multiplication and division mechanisms used in Naval computers. Although special forms of multipliers may be encountered, the principles developed in this section should prove helpful in analyzing their operation.

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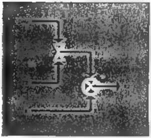
Here is a way a multiplier can [illegible] used in conjunction with a differential to solve a simplified fire control problem. In the above illustration, the target [illegible] [illegible] a present range R and the ships are moving so that R [illegible] increasing at a range rate DMr. [illegible] order to hit the target, the gun must be aimed to account for the change [illegible] range Rp2 during the time the projectile is in flight T2. Rp2 (called the range prediction) [illegible] computed by obtaining the product DMr · T2. The future range R2 at which the target will be hit [illegible] found by adding Rp2 to R. At the right is a schematic of a mechanism for performing these calculations.



problems

1. Work out schematics for computer mechanisms employing multipliers to accomplish the mathematical operations listed at the right.

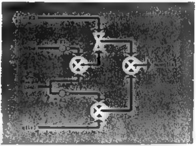
   a. Obtaining as an output the square of an input A.

   b. Obtaining as an output the reciprocal of an input A.

2. Examine the schematic at the right and determine expressions for the outputs of the multiplier and the differentials. Then simplify the expression for the output of the final differential to show that the equation for mwq(Ls) can be written as:

$$\mathrm{mwq(Ls)} = \mathrm{K1Wba}\left[\frac{\mathrm{T2}}{\mathrm{R3}} - \mathrm{K2}\right] + \mathrm{DMb}\left\{\frac{\mathrm{T2}}{\mathrm{R3}} - \mathrm{K2} + \mathrm{K3}\right\} + \mathrm{q(Ls)}$$

This equation forms a part of the computations performed in an actual Naval fire control computer.



3. [illegible] the same computer mentioned in the second problem, the advance range R3 is determined by modifying the generated present range c(R) to account for target motion during the projectile time of flight, wind effect on the projectile, variations in the initial projectile velocity, and range spot corrections. The equation for advance range is as follows:

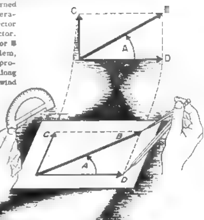
$$\mathrm{R3} = \mathrm{c(R)} + \mathrm{q(R)} + \mathrm{u(Rp3)} + \mathrm{K3(DMr)uj} + \mathrm{T2}\{\mathrm{K}[(\mathrm{DMr})\mathrm{uj} + \mathrm{K1Wra}]\}$$

First construct a black box diagram and then draw a schematic diagram for a mechanism to solve the equation. Use one multiplier, five differentials, and gear ratios for K, K1, and K3. Arrange the schematic for clarity.

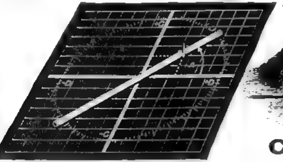
SECTION 3

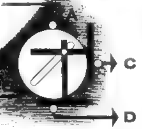
TRIGONOMETRIC DEVICES

Computers used in Naval weapons systems often must deal with problems involving trigonometry. Ordinarily, these problems are concerned with the solution of right triangles, particularly as applied ■ operations with vectors. The basic operations include resolving a vector into components and combining vectors to produce a resultant vector. Illustrated at the right is a typical vector diagram showing a vector ■ and two perpendicular components C and D. ■ a practical problem, vector B might represent the velocity of the wind affecting the projectile, and vectors C and ■ the components ■ the wind velocity along and across the line of fire, while angle A is the direction of the wind with respect ■ the line of fire.



Problems such as the one above can be handled with written computations or may ■ set up by simply drawing the vectors to scale. The latter method is straightforward and ■ very convenient. Once the diagram has been constructed, any vector or angle can be obtained by direct measurements. Instead of actually drawing the vectors, it ■ possible to set up the problem mechanically by using an elementary graphical device that ■ very similar to the one described for multiplication ■ the preceding lesson.



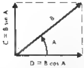


$$C = B \sin A$$

$$D = B \cos A$$

This elementary graphical device employs a sheet of graph paper, a pivoted rod, and a sliding indicator pin as before. However, ■ this case, two scales have been added: one to indicate the angle of the rod, and the other to show how far the indicator pin ■ moved from the pivot. To use the device for obtaining the components of a vector, proceed as follows: Set up the vector by rotating the rod to angle A and moving the indicator pin out along the rod to a distance B. The component vectors C and D can now be determined by reading the position of the pin on the C and D scales. Note that this ■ essentially the mechanical equivalent of actually drawing a diagram.

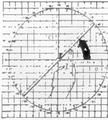
SCOPE OF SECTION. The remainder of this section ■ devoted to a detailed explanation of how the resolution and combination of vectors are accomplished by means of mechanical devices. Starting with the elementary graphical device, the details of mechanisms used in Naval computers are developed and analyzed. A number of practical applications and illustrative problems are given at the end of the section.



Since the graphical device produces a mechanical equivalent of the above diagram, the device can function either to resolve a vector into two components or to combine two vectors into their resultant vector. Which of these actions occurs depends on what values are selected as inputs and outputs. As can be seen from the diagram, the three vectors form the sides of a right triangle. Accordingly, the device can be used to set up and solve right triangles in the same way as it solves vector problems. In the complete triangle any two of the four values A, B, C, and D can be used in inputs to obtain the other two values as outputs. The manner in which the device functions in the resolution and combination of vectors (or in the solution of triangles) is shown at the right.

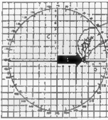
resolution of a vector

The first step in the resolution of a vector into its components is to establish the direction of the vector. This is done by rotating the rod to the desired direction as represented by input angle A. In the case illustrated, the D axis is used as the fixed reference line from which angle A is measured. The positive direction for A is taken as counterclockwise.



combination of vectors

To find the resultant of two perpendicular vectors C and D, proceed as follows: With the rod at zero degrees, slide the indicator pin out from the pivot until the reading on the D scale is equal to the scalar magnitude of vector D. This setting establishes the D vector in the device by setting up its magnitude and direction. (The positive direction for D is taken to the right of the C scale.)

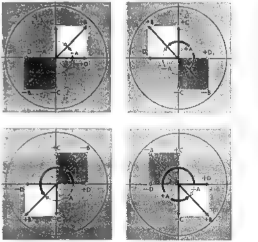


positive and negative values

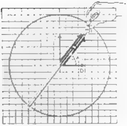
In trigonometry, only positive values of radius are usually recognized. However, in fire control, vectors and components must often be combined. Therefore, a convention of signs must be established so that directions are properly accounted for in scalar additions.

The relationship between the signs of the various values that would be read on the scales of a trigonometric device is shown in the diagrams at the right. The heavy lines show the pattern of signs for a positive value of B in each of the four quadrants. The positive direction of the B vector is defined by angle A. Angle A itself is measured from the plus D axis and is positive when measured counterclockwise; negative when measured clockwise. Note that a given direction of B can be defined by either a positive value of A or a negative value. As shown in the first figure, an angle A of +45 degrees defines the same direction as an angle A of -315 degrees (45 - 360 = -315).

The signs of component vectors C and D for a positive value of B depend on the quadrant to which angle A is measured. These signs follow the same quadrant rules as apply to the sine and cosine of the angle. When vector B is made negative by reversing its direction, the signs of component vectors C and D also reverse. This condition is shown by the dotted vectors in the figures.



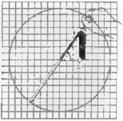
The length of the vector is set into the device by sliding the indicator pin out from the pivot by the distance B. This distance represents the scalar magnitude of the vector. Since both the magnitude and direction of the vector are now set in, the representation of the vector is complete. To obtain the two components, [redacted] only necessary [redacted] read their values on the C and D scales. The C value is read by tracing horizontally across from the pin, and the D value by tracing vertically downward from the pin.



C =

D =

The C vector is set [redacted] by moving the indicator pin up vertically until its distance above the [redacted] axis is equal to the scalar magnitude of vector C. (This movement causes the rod to rotate about the pivot. Since the pin moves in a vertical path, it must slide outward along the rod [redacted] keep the D vector constant.) After the C value has been set in, the angle A of the rod and the distance B define the direction and scalar magnitude of the resultant vector. This [redacted] the sum vector of vectors C and D.



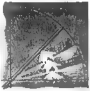
$\vec{B}$ =

A =

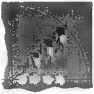
Input-output movements

The preceding analysis shows that the elementary graphical device for trigonometric operations has four basic mechanical movements. These movements are illustrated separately [redacted] the figures below. Any actual computing device employing this principle must be able to reproduce the four movements. Variations may be expected in the design [redacted] the individual mechanism producing the movements, but in all cases the principle remains the same regardless of mechanical detail.

1. A rotation of the rod about the origin measured counterclockwise from the +D axis.

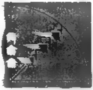


3. The motion of the indicator pin measured parallel [redacted] the D-axis.



[redacted]. A movement of the indicator pin measured along the rod from the origin.

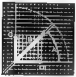
4. The motion [redacted] the indicator pin measured parallel [redacted] the C-axis.

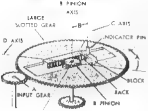


Summary

Computing mechanisms that are designed to resolve a vector into components are called component solvers while those that combine two vectors to produce their resultant are known as vector solvers. Both these types of mechanism are based on the principles that have been developed. Next we will consider how these mechanisms are designed to reproduce the four basic movements inherent in the elementary trigonometric device.

Construction of a typical trigonometric device

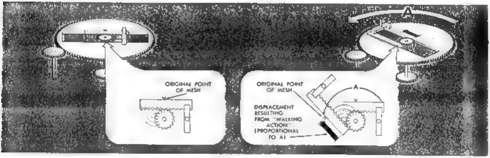




In a typical trigonometric device the function of the rod of the graphical computer is performed by a slot cut into a large gear that is driven through angle A. The indicator pin is mounted on a block that slides in the slot. A rack attached to the block is driven by the B pinion to move the pin back and forth in the slot. The axis of the pinion shaft is at the center of rotation of the slotted gear. The bearing supports for the slotted gear are not shown in the figure. These supports are incorporated in the mounting plate for the complete mechanism and hold the slotted gear so that it rotates accurately about the axis of the B pinion shaft. A gear on the pinion shaft and a gear meshed with the slotted gear provide for making external connections to the mechanism.

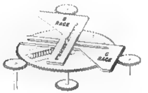
The direction of vector B is set up by rotating the slotted gear until the slot is at angle A with respect to the reference line (in this case, the D axis). The scalar magnitude of vector B is put in by rotating the B pinion. As it rotates, the pinion drives the rack causing the indicator pin block to slide in the slot. The distance of the indicator pin from the axis of rotation as measured along the slot establishes the scalar magnitude of the B vector. Since the slot extends across the entire gear, both positive and negative values of the B vector magnitude can be set into the mechanism.

compensating differential

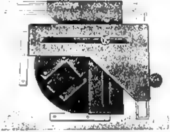


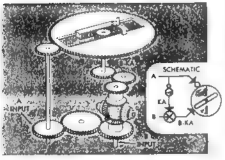
Up to this point we have not considered a problem that arises with the indicator pin mechanism described above. Assume the mechanism is initially set up as shown above with the indicator pin at some definite position. Now suppose we wish to change the angle A input without changing the B setting. The natural thing to do would be to rotate the slotted gear to the new angle A while holding the B pinion fixed. However, as the rack is carried around with the slotted gear, it rolls around the fixed B pinion. As the rack rolls, the rack teeth (shown numbered in the enlarged views) successively engage the corresponding tooth spaces of the fixed B pinion. The change in the point of mesh caused by this "walking" action causes the rack to slide in the slot so that the pin moves outward from the center of rotation by an amount proportional to the change in angle A. Thus the B setting changes in spite of the fact that the B pinion is held fixed. Since changes in angle A affect the B setting, errors will result if compensation is not made for this effect.

Now that the B vector has been set up, it is only necessary to provide mechanisms for picking off the C and D component vectors. This is done by means of slotted racks similar to those used ■ multiplier mechanisms.



Since the rack and pinion mechanism is reversible, the C and D racks can be used as inputs and the A and B values as outputs. Therefore, the mechanism just developed could be used either to resolve a vector into two components (as a component solver) or ■ combine two vectors to produce their resultant vector (as a vector solver). The mechanism shown here ■ an actual unit that is used as a vector solver in a Naval fire control computer.

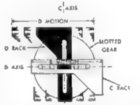




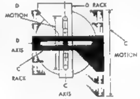
Since the error in the B setting ■ proportional to the A input, the error can be eliminated by simply subtracting a value proportional ■ A from the B input. We have already seen that a differential can be used ■ perform subtraction. The differential can be connected as shown above, so that the B input drives the spider, and the A input drives one end gear through the necessary gear ratio to obtain the required proportion of A. The output from the other end gear (B-KA) ■ used to drive the B pinion.

zero position

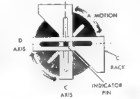
When angle A is at zero or 180 degrees, the gear slot is aligned with the B axis. Accordingly, the B and D values can vary over their entire range without moving the C rack off zero.



Similarly, when angle A ■ at 90 or 270 degrees, the gear slot is aligned with the C axis. Now the B and C values can vary over their entire range without moving the ■ rack off zero.



With B at zero, the indicator pin is at the axis of rotation of the slotted gear. Therefore, angle A can be varied over a full 360 degrees without moving either the ■ rack or D rack off zero.

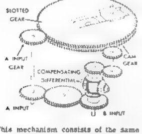


SUMMARY

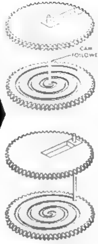
All devices of the general type described here employ two slotted racks for the C and D vectors. However, the mechanism for positioning the indicator pin may take various forms. On the next page we will cover several other indicator pin mechanisms.

HERE ARE SOME OTHER DEVICES COMMONLY EMPLOYED AS . . . . . . **. . . INDICATOR PIN POSITIONING**

cam type



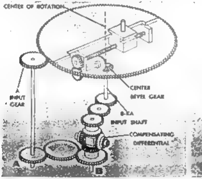
This mechanism consists of the same slotted gear as before with the addition of another gear of the same size having a spiral cam groove. The cam performs the same function as the rack and pinion in moving the indicator pin to set up the scalar magnitude of the B vector. Note that to keep the B input independent of the A input this mechanism also requires a compensating differential. The cam gear and the slotted gear are actually mounted close together as shown above. In the figures to the right, the gears have been separated in order to clearly show how the cam moves the pin.



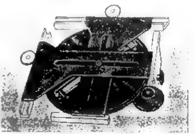
Projecting from the bottom of the indicator pin block is a follower that engages the cam groove. The action of the follower and groove is similar to the action of a phonograph needle in the groove of a record. As the cam is rotated ■ the B input, the follower rides ■ the groove thus moving the indicator pin along the slot. In the upper figure, the follower is shown near the center of the cam as is the case for a small value of B. In the lower figure, the cam has been rotated counterclockwise about 2-1/2 revolutions to position the indicator pin so as to produce a larger magnitude for vector B. Note that since the cam groove progresses outward from the center of rotation the travel of the indicator pin is limited to somewhat less than one half the diameter of the cam gear. Also, the pin can only move out from the center in one direction. Therefore, the mechanism ■ limited to handling either positive B values or negative B values. Shown to the right is a modification of the indicator pin block that makes it possible ■ handle both positive and negative values of B.

screw type

In the screw type mechanism, the indicator pin block is threaded to receive a lead screw. The lead screw is driven by gearing as shown in the figure at the lower left. Since the gearing for the lead screw must be carried around with the slotted gear, the B input shaft ■ mounted concentric with the center of rotation. Because of the rolling action that would occur at the center bevel gear when the slotted gear is rotated by an A input, a compensating differential must be inserted into the ■ input gearing. By subtracting a value proportional to A from the B input, the differential produces the required compensation as explained on the preceding page. Since the slot in the gear extends all the way across on both sides of the center of rotation, the mechanism can handle positive and negative values ■ B.



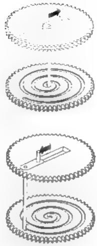
Shown below, is an actual screw type trigonometric device used in an anti-aircraft computer for determining range and elevation components of vertical target speed.



MECHANISMS

To permit handling both positive and negative B values, the indicator pin block is elongated and the indicator pin is offset from the cam follower by a distance equal to one half the total cam travel. When the follower is at the center of the cam as shown here, the indicator pin is at one extreme of its motion. (Assumed here to be positive.) As the cam rotates counterclockwise, the pin moves toward the center decreasing the size of the B vector.

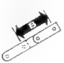
As the cam continues to rotate, the pin crosses over center and the sign of the B vector changes from positive to negative. When the follower reaches the outer edge of the cam groove as shown in this figure, the pin is at its maximum negative position. Note that the total cam travel is the same as for the pin having no offset. However, because of the + and - feature, the B vector can now be only one half as large as before.

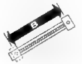


Shown above is an actual cam type trigonometric device used as a component solver in a Naval fire control computer. Note that except for the fact that a cam is used to position the pin, its appearance is essentially the same as that of the vector solver previously illustrated.

limitations

The range of the B input for a given diameter of the slotted gear is determined by the type of mechanism used to position the indicator pin. The diagrams at the right compare the screw type with the offset pin cam type. Since the total pin travel is limited to slightly less than one half the cam diameter, the range of B is much smaller for the cam type than for the screw type.



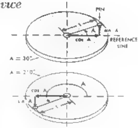


It is important to realize that screw and cam type mechanisms cannot be driven in reverse. That is, unlike the rack mechanism, applying a force to the indicator pin will not cause the B gearing to rotate so as to produce an output. Therefore, the screw type and cam type mechanisms can only be used for component solvers and not as vector solvers.

summary

The trigonometric mechanisms covered to this point all operate by setting up an actual graphical representation of the problem to be solved. Other devices that differ slightly in mechanical detail may be encountered in Naval weapons systems, but all can be analyzed in essentially the same way. On the next page we will take up another such device, and then consider how trigonometric devices can be employed in solving weapons systems problems.

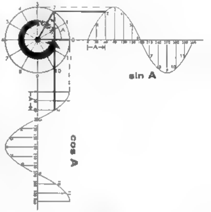
RESOLVERS .... another type of trigonometric device



Some trigonometric devices, instead of handling vectors, generate sine and cosine functions directly for use in computations.
Such devices are called RESOLVERS.

GENERATION OF SIN A AND COS B

Sine and cosine functions can be generated simply by a pin located at a fixed distance of one unit from the center of rotation of a disc. As shown to the right, for any given angle A from the reference line, the height of the pin above the line is equal to sin A and the distance from the center measured along the reference line is equal to cos A.



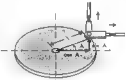
The manner in which the height of the pin above the reference line varies with angle A can be seen by plotting the height against angle A in rectangular coordinates. The horizontal axis of the graph is graduated in values of angle A. The height for all values of A can be obtained from a diagram of the actual pin motion drawn with its reference line along the horizontal axis of the graph. For each angle, the height of the pin is projected horizontally to the ordinate for that same angle. As shown in the diagram, the curve produced by rotating the pin through one one full revolution is the familiar sine curve.

The cosine curve can be generated in a similar way by setting up rectangular coordinates 90 degrees from the set described above. Now as shown at the right, the cosine component for each angle can be drawn into the graph by projecting the pin position vertically downward to the proper ordinate. By looking at the resulting graph from the left side of the page, it can be seen that it is an ordinary cosine curve.

RESOLVER MECHANISMS

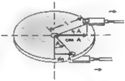
Described below are two elementary resolver mechanisms that utilize the foregoing principle.

one pin resolver



The mechanism shown at the right has two links at right angles that are attached to the pin to pick off the sine and cosine components of the unity vector. This mechanism acts just like a component solver with the indicator pin set to a fixed distance of one unit from the center of rotation. The links perform the same function as the output racks of the component solver.

two pin resolver



Here two pins are used, mounted 90 degrees apart, at a fixed distance of one unit from the center of rotation. In this case the two links move in the same direction to pick off the sine and cosine functions of angle A. As shown in the diagrams, angle A is measured from one reference line for cos A, and from another reference line 90 degrees away for sin A. Note that with these references, the signs of the functions still change in accordance with the standard rule as A is varied through the four quadrants.

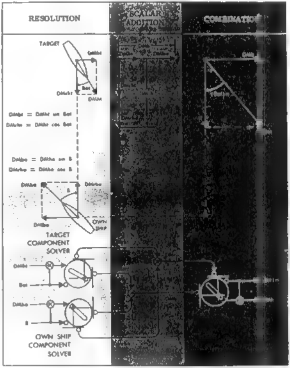
RESOLVER-MULTIPLIER COMBINATION

For example, a resolver can be employed in combination with a multiplier to perform trigonometric computations similar to those performed by a component solver. In the diagram only the cosine function is used thus producing the same output as is obtained from the cosine rack of a component solver. In some Naval computers, particularly those of the linkage type, combinations of resolvers and multipliers are used not only for resolving vectors but for a variety of other trigonometric operations.

APPLICATIONS

One of the most common applications of trigonometric devices is in the resolution and combination of velocity vectors describing the motion of own ship and target. The components of own ship and target speed that are of particular interest are those measured alongthe line of sight and measured perpendicular to the line of sight. The components measured along the line of sight affect the range and the components across the line of sight affect the bearing. The combined motion of own ship and target is called their relative motion. The relative motion represents the way in which the target moves with respect [redacted] own ship.

RELATIVE MOTION PROBLEM



In the example at the right, own ship speed [redacted] DMho and the target is at a relative bearing B. The target [redacted] moving at a speed DMht, and its speed is directed at a target angle Bot [redacted] the line of sight. The components of DMho are DMrho and DMbo, while the components [redacted] DMht are DMrht and DMbt. They are computed according to the equations accompanying the figures. Directly below the two ships, two component solvers are shown, one for own ship and one for the target. These component solvers perform the computations called for by the equations.

Range rate DMrh is obtained by combining DMrho and DMrht. Since these two vectors are parallel to each other, this can be accomplished [redacted] simple scalar combination. Linear bearing rate DMb is obtained from DMbo and DMbt in a similar way. These scalar combinations are performed by two differentials as shown [redacted] the figure. Note that the pattern of signs selected [redacted] such as to produce DMrh and DMb vectors of the correct magnitude and direction.

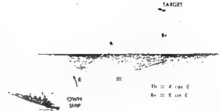
[redacted] the total relative motion vector DMh [redacted] desired, it can [redacted] obtained by combining DMrh and DMb [redacted] a vector solver. The outputs [redacted] the vector solver are the total relative motion velocity vector DMh and the relative motion target angle (Bot)m.

summary

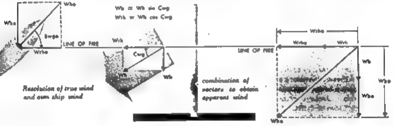
The preceding pages have developed the principles of basic mechanical devices for performing trigonometric operations in computers. These principles apply not only to the resolution and combination of vectors but also to operations involving right triangles and the solutions of trigonometric equations in general. Some problems are given on the next page to illustrate the use of trigonometric devices in naval computers.

PROBLEMS to be solved . . .

1. Having the slant range to the target R, and the target elevation measured above the horizontal E, it is sometimes necessary to determine the height of the target above the horizontal Rv and the horizontal range to the target Rh. The quantities are related as shown by the equations accompanying the space diagram at the right. Draw the schematic diagram of the mechanism for solving the equations. Also show how a resolver and two multipliers can be employed to do the same job.



2. Computations involving the effect of wind on the projectile appear in naval fire control computers. The problem is similar in many ways to the relative motion problem described on the preceding page except that the line of fire rather than the line of sight is used as a reference for resolving and combining the vectors. Besides the actual true wind, the motion of own ship creates an additional wind that is in effect blowing opposite to own ship motion. The combination of true wind and own ship wind produces the apparent wind affecting the projectile. Analyze the vector diagrams and equations below to see how the horizontal components of the apparent wind are obtained. Starting with inputs of Who, Bwgo, Wh, and Cwg, draw the schematic diagram of the computing system used to obtain Wrha and Wba.

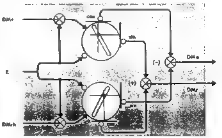


Resolution of true wind and own ship wind

combination of vectors to obtain apparent wind

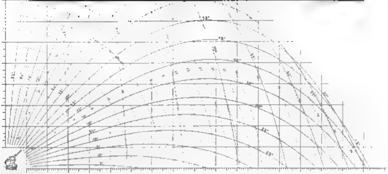
3. To complete the wind problem, Wrha is further resolved to find its components affecting slant range and elevation. These two components are range wind rate Wra and elevation wind rate Wea. To obtain these components, Wrha (which is at an angle Eg with the line of fire) is resolved into components along and perpendicular to the line of fire. Add the schematic diagram for the required mechanism to the diagram of problem 2.

4. In one type of Naval computer, linear elevation rate DMe and range rate DMr are obtained from inputs of rate of climb DMv, horizontal range rate DMrh, and target elevation E. These computations are performed by two component solvers and two differentials as shown to the right. Study the diagram and write the equations for the outputs of the two component solvers and the equations for DMe and DMr. After obtaining the equations, draw a space diagram illustrating this problem.



SECTION 4

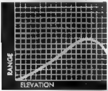
devices for directly obtaining FUNCTIONS OF VARIABLES

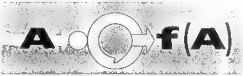


B = f(A)

[redacted] weapons systems, it [redacted] often necessary to perform computations involving a quantity equal [redacted] a function of some variable. In many cases, [redacted] is possible to compute the functions but in others, the relationship between the independent and dependent variables can only be obtained from experimental data. For example, the ranges to which a gun will fire for various elevation angles can only be obtained from actual firings and are recorded in books of range tables. For fire control calculations performed on paper, the required values can be looked up in the tables and entered into the computations. Another method for handling such functions [redacted] to plot the experimental data on a graph. The graph can then be used to obtain any required value.

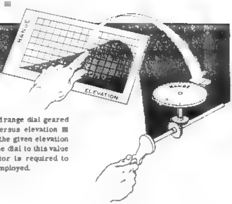
The two methods described above are not suitable for mechanical computations. In Naval computers it is necessary to have the data built into some device that makes the data accessible automatically. [redacted] the following pages we are going to cover a number of devices used for this purpose in weapon system computers. These devices include special dials, cams, and function generators.





[illegible] situations where functions of variables are set manually into a computer, the value of the function can be established by the use of dials or scales. Shown here are several methods that can be employed for setting data into a computer. In the following examples it [illegible] assumed that gun elevation [illegible] known and that it is desired [illegible] set in the corresponding range.

DIALS AND SCALES

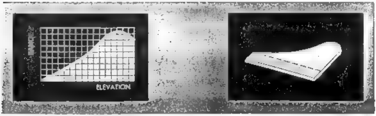


One method would be to use a uniformly graduated range dial geared to the input shaft. A table or a graph of range versus elevation [illegible] used to find the value of range corresponding [illegible] the given elevation angle. The range input crank is turned to bring the dial to this value of range. Since for each new setting the operator is required to again read the graph, this method [illegible] not widely employed.

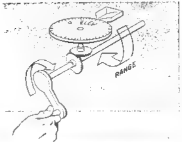
CARTESIAN CAMS

A device for producing the value of a function automatically may be developed directly from the graph of the function as drawn in cartesian coordinates. The heart of the device [illegible] a metal plate shaped so as [illegible] form a cam. The cam plate is formed by transferring the curve from the graph to the plate and then cutting the plate to form a cam surface corresponding to the curve. The cam plate can be made to any convenient scale. Since the cam plate is an exact replica of the graph, the height of the curved cam surface at any point [illegible] a physical representation of the value of the function. Distances measured along the cam parallel to its base physically represent the value of the independent variable. Shown to the right [illegible] a complete mechanism that utilizes the information cut into the cam plate.

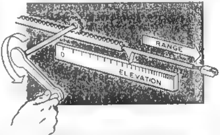
Shown below is a graph of range R versus gun elevation E and the equivalent cam plate.



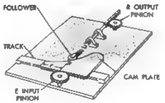
A more direct operating method can be achieved by using a specially calibrated dial on the range input. The dial is graduated in units of elevation, but the shaft position for each graduation is made equal to the corresponding range value. Since the relationship between range and elevation is not linear, the distance between graduations will not be uniform. With such a dial, the operator need only position it to read the given value of elevation. The shaft rotation into the computer is then equal to the corresponding range.



In some computers, particularly linkage types, values are expressed as linear displacements rather than as shaft rotations. For such computers, a straight scale can be used to perform the same functions described for dials. The figure shows a non-linear elevation scale being used to set range into a computer. Note the manner in which the dial graduations crowd at high values of gun elevation.



A rack is cut into the bottom of the cam plate and the plate is mounted on a track so that it can be moved back and forth by the E input pinion. A roller type follower is mounted so as to pick off the R output corresponding to the E input. The R output is connected to the external gearing through a rack on the follower.

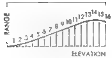


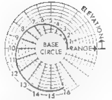
It can be seen that this device can receive any E input and produce the associated value of R as an output without any necessity for referring to graphs or tables or for reading dials. Because such a device can automatically and continuously produce any desired function of a variable, cam devices have wide applications in all types of weapon system computing equipment.

summary

The devices just developed illustrate principles universally employed in computers for handling a wide variety of empirical and mathematical functions. Although all cams operate according to the same general principle, they can differ greatly in the form of their construction. The following pages of this section cover the more common cam mechanisms encountered in weapons systems, and give explanations of their design characteristics. As will be seen, the only significant differences in these mechanisms are in the type of cam working surface employed and in the design of the follower mechanism.

POLAR CAMS

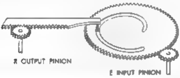




A function of a variable can be plotted in polar coordinates as well as in cartesian coordinates. Shown above is the same cartesian graph of range versus gun elevation as described on the preceding page. At the right is the same function plotted in polar coordinates. In the polar plot, gun elevation is represented by the angle of the radius vector and range is represented by the vector length. Each numbered vector in the polar plot corresponds to a similarly numbered ordinate in the cartesian plot.

The curve above is slightly different from an ordinary polar graph. Instead of being plotted from the center, the range values are measured outward from a base circle. The reason for this is explained to the right.

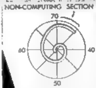
CAM WORKING SURFACES



The working surface against which the follower bears need not take the form previously described. Almost any kind of surface could be used. Another type of working surface that is widely used is shown to the left. In this mechanism, the curve is in the form of a groove cut in the surface of the cam gear. Note that since the follower is restrained by the groove, no spring is required.

COMMON TYPES OF CAMS

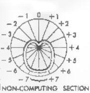
There are a number of mathematical operations that appear frequently in fire control computations and can be handled conveniently by means of cams. In addition, cams are commonly used to convert a simple motion, such as a rotary or linear motion, into some other form. For example, a cam can be used to change a rotation into an oscillating up and down movement. In such operations, the function of the cam is primarily mechanical rather than computational. Shown to the right are some grooved cams that appear frequently in Naval fire control computers. The tables accompanying the illustrations show the actual values produced by the cam for various angular positions.



DEG	TAN
70	2.75
65	2.14
60	1.73
55	1.43
50	1.20
45	1.00
40	.84

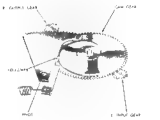
TANGENT CAM. The output of this cam is the tangent function of the input angle. Note that the range of the angles must be limited because the tangent goes to infinity at 90 degrees. Similar cams exist for all the trigonometric functions of angles.

NO	SQ
1	1
2	4
3	9
4	16
5	25
6	36
7	49



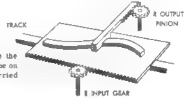
SQUARE CAM. This cam produces the square of the input quantity. Since the square of either a positive or a negative quantity is always positive, the groove in the cam plate is symmetrical. Such cams can be cut for other powers or roots.

As was the case with the cartesian cam, a polar cam is made by cutting a metal plate to the shape of the polar graph. The cam is mounted on a gear so that it rotates about the center of the base circle. A follower roller mounted in a spring loaded sector gear rides along the edge of the cam. The motion imparted to the follower, as the cam is rotated by the E input, is the value of the associated range output R. This output is transmitted to the external mechanism through the R output gear. Note that because the cam curve was plotted on a base circle, the follower does not move to the center of rotation when range becomes zero. This fact makes for smoother action over the entire cam surface. The cam mechanism in the photograph is one actually used in a computer.



A cam groove can also be cut into the side of a cylindrical cam body.

Instead of a groove, the cam surface can also take the form of a raised surface or ridge. The ridge can be on a sliding plate as shown to the right, or can be carried on a rotating disc or drum.



NO	RECIP
1	1.00
2	.50
3	.33
4	.25
5	.20
6	.17
7	.14

RECIPROCAL CAM. A frequently used method for dividing in computers is to multiply by the reciprocal of the quantity. The action of this cam is limited because the reciprocal of a small value is very large and that of a large value is near zero.

CONSTANT LEAD CAM. This cam has a "constant lead". That is, the movement of the follower in and out from the center is directly proportional to the input quantity. In effect, this cam merely converts rotary motion to linear motion.

summary

Up to this point we have covered the principles of basic cam devices used to produce mathematical or empirical functions of one independent variable. Regardless of how complicated the function is, a cam may be cut on the basis of the graph of the function. This makes the cam a very useful device in mechanical computation. Once a set of data or a functional relationship has been cut into a cam, this information can be readily utilized on a continuous and automatic basis. The cams just discussed all handle functions involving one independent variable. On the next page a cam device is developed that can produce a function of two independent variables.

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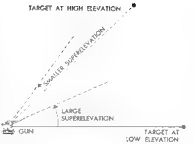
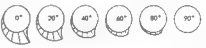
CAM FOR A FUNCTION OF TWO VARIABLES

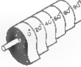
In weapon system computations, quantities are sometimes encountered that are empirical functions of two separate and independent variables. For example, a gun must be elevated above the line to the future position of the target by an angle that accounts for the amount the projectile drops due to gravity during time of flight. This angle is called superelevation b(Vs), and its magnitude depends on both elevation and range. The greater the range, the greater b(Vs) must be. However, for any given range, b(Vs) decreases as elevation increases. The data defining the relationship of b(Vs) to range and elevation can only be determined from experimental firings. Such empirical data can be handled conveniently by means of a cam device. Since b(Vs) depends on two variables, it is necessary to employ a special type of cam mechanism.

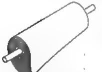


For any one elevation angle, it is possible to cut an ordinary flat cam to produce b(Vs) as a function of range. However, a separate cam would be required for each elevation angle. Note in this series of cams, that the cam throw (shaded area outside base circle) decreases from a large value at zero degrees to zero throw at ninety degrees.

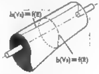


The separate cams could be mounted on a common shaft driven by the range input and the follower moved from cam to cam as elevation changes. However, this would not be really practical because elevation could be handled only in a limited number of steps.



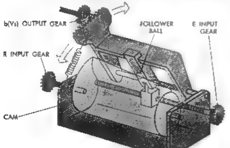


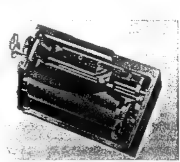
To provide for a continuous elevation input, a cam can be cut from a solid piece that progresses smoothly from one end to the other. The effect is equivalent to an infinite number of thin plate cams for angles ranging from zero degrees through ninety degrees of elevation.



A lateral section through the cam gives the variation of b(Vs) with range for the selected elevation, while a radial longitudinal section gives the variation of b(Vs) with elevation for the selected value of range.

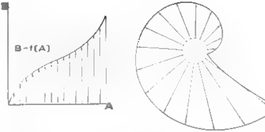
The cam just described is used for a number of functions in Naval computers. (One computer uses four such cams.) These cams are usually called three dimensional or barrel cams. The illustration below shows how the follower is positioned lengthwise on the cam by a lead screw moved by the elevation input. The cam itself is rotated by the range input. The follower moves a swinging frame, and a gear segment on the frame drives the b(Vs) output gear. The photograph shows an actual barrel cam mechanism.

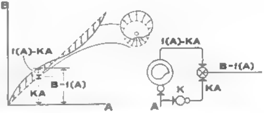




STRAIGHT LINE APPROXIMATION

If the ordinates for the curve of a function are used directly [redacted] cutting a cam, the cam can sometimes have a rather large throw as shown to the right. Cams of this type may be excessively bulky and be subject to operational difficulties caused by such factors as steep or sharp contours. These difficulties can be overcome by a simple expedient. A straight line is drawn along the curve so as to approximate the major portion of the function. In the mechanism, the ordinate of the straight line function can be produced by a simple gear ratio that multiplies the independent variable by a constant. Now the cam need only produce the difference between the ordinates of the straight line and of the curve representing the function. Since these differences are small, the cam will have a small throw. The outputs of the gear ratio and of the cam are combined [redacted] a differential to produce the total function. (Compare the sizes of the two cams; both are drawn to the same scale.)





NOTES ON CAM DESIGN

precision construction

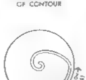
To function effectively, a cam must be designed not only to incorporate the required data but also to operate properly [redacted] a mechanical device. Excessively steep curves and sharp changes in contour may result in the necessity for high operating forces and may cause undue wear. To operate smoothly and accurately, the cam should preferably [redacted] nearly round, and should be designed when possible with rolling contact between the follower and the cam rather than rubbing contact. For these reasons, cams mechanisms found in computers are more carefully and elaborately constructed than those used in conventional machinery.

PREFERRED TYPE OF CONTOUR

UNDESIRABLE TYPE OF CONTOUR

runout

Sometimes a function [redacted] such that a cam cannot cover the entire range of the function. (For example, the tangent of an angle goes [redacted] infinity at 90 degrees.) Therefore the cam is cut for values between certain limits. When these limits are exceeded, the follower enters a non-computing section of constant radius called a "runout". While the follower [redacted] in the runout section, the output remains constant.



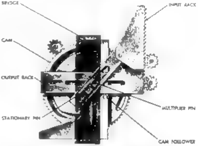
SUMMARY

Cams represent one of the most widely used methods employed for obtaining functions of variables. Although they are usually used as separate computing units, cams may be built into other computing mechanisms. Also, there are mechanisms other than cams used for generating functions of variables and which operate on a different principle. Next we will consider some computing units having cams built into them, and then will take up function generators.

In some cases, one or both of the inputs to a computing mechanism is a function of a variable rather than the variable itself. Such an input can be handled by having a separate cam mechanism which receives the variable as an input, and whose output is fed to the computing mechanism. However, for compactness and overall simplification of the computer, it may sometimes be desirable to incorporate cams directly into the construction of the computing device. There are many examples of this type of design in Naval computers. Shown below are three widely used types of computing mechanisms employing built-in cams.

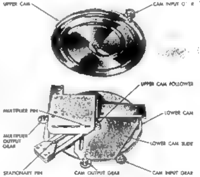
SINGLE CAM COMPUTING MULTIPLIER

In this multiplier, a cam is used (instead of a rack or screw mechanism) to position one of the slotted input slides. The cam may be cut so that the motion of the slide [illegible] any desired function of the input. Except for this difference, the action and geometry of the mechanism is the same as that described for multipliers in section 2.



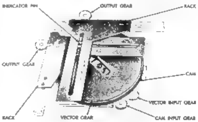
TWO CAM COMPUTING MULTIPLIER

Cams can also [illegible] used to put both inputs into a multiplier. The illustration at the right shows the upper cam lifted to expose the inner mechanism of the multiplier. The geometry established by the slots is again the same as explained in section 2. The mechanism illustrated here has a special feature in that the slide moved by the lower cam is provided with a rack that drives a cam output gear. Thus, the function produced by the cam can be taken off as an additional output.



COMPUTING CAM COMPONENT SOLVER

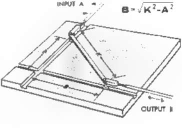
Normally the cam used in a component solver [illegible] of the constant-lead type that merely converts the vector magnitude input from a shaft rotation to a linear movement of the indicator pin. However, in the component solver shown here, a computing cam is used [illegible] position the indicator pin. The cam is cut to produce an indicator pin displacement that is proportional to the reciprocal of the vector magnitude input.



Another method for producing a function of a variable is through the use of a mechanism that sets up a graphical or geometrical analog of the function. This is an operating principle similar to that of the trigonometric devices described in section 3. Basically, these devices mechanically set up a geometric diagram in which lines and angles represent the parts of the function to be generated. The equations expressing the relationship between the lines and angles of the diagram are the same as the function. For example, the sine and cosine functions can be generated by a simple device that mechanically sets up a right triangle having a hypotenuse equal to unity; the legs of the triangle then being equal to the sine and cosine of the angle.

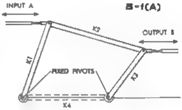
GUIDED BAR LINKAGE

Assume that in a computation, an expression of the form $\sqrt{K^2 - A^2}$ appears. This expression can be handled simply if it is remembered that in a right triangle having legs A and B and hypotenuse K, $K^2 = A^2 + B^2$ or $B = \sqrt{K^2 - A^2}$ (Pythagorean theorem). At the right is a mechanism that sets up a right triangle whose hypotenuse is represented by a bar of constant length K. The ends of the bar are guided by two slots at right angles. Input A and output B are connected to the bar by means of links.



THE FOUR BAR LINKAGE

This mechanism actually has three moving bars, the fourth bar being represented by the distance between the fixed pivots. Although the mechanism is quite simple mechanically, the functional relationship between A, B and the constant lengths of the bars can be quite complicated. By properly adjusting the lengths of the bars and the initial angles, the graph of B as a function of A can be controlled so as to approximate a wide variety of functions. Mechanisms of this type find considerable application in computers of the linkage type.



NON-CIRCULAR GEARS

Although non-circular gears are not widely used, it is possible to design gears of almost any shape. Generally as non-circular gears rotate, the radii measured from the center of rotation to the point at which the gears mesh undergo a variation. This means that the driven gear will not rotate uniformly but its rotation will be some function of the input gear rotation. By properly designing such gears, a wide variety of functions can be generated.

summary

As has been demonstrated in this section, devices for producing functions of variables can take many forms including dials, scales, cams of several types, and many kinds of function generating mechanisms. In analyzing the action of all such devices, it is important to remember that they are nothing more than a means for mechanically reproducing the information that would be given by the graph or tabulation of the function. Following are problems illustrating the principles covered in this section.

PROBLEMS

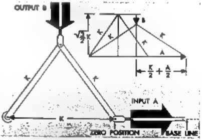
1. Each time a gun is fired there is a slight erosion of the bore that causes gradual enlargement. After a number of firings, this results in greater and greater loss in the initial velocity at which the projectile leaves the gun thus decreasing the range. In solving the fire control problem this loss in velocity must be taken into account. The table shows the velocity loss in feet per second (VL) as a function of the number of equivalent service rounds fired (ESR) for a 5"/38 caliber gun. Using these data, plot a graph in cartesian coordinates showing how the velocity loss varies with the number of rounds fired. Sketch a cartesian cam mechanism based on this curve.

ESR	VL	ESR	VL
100	6	900	97
200	26	1000	102
300	42	1100	107
400	56	1200	111
500	66	1300	115
600	76	1400	117
700	84	1500	120
800	91	1600	122

2. Again using the data given in the table for problem 1, plot a polar coordinate graph showing velocity loss in feet per second as a function of equivalent service rounds fired. For plotting the graph, the following scales are suggested: 20 degree angle for each 100 ESR, and one inch for 100 feet/sec. of velocity loss. Use a base circle one inch in diameter. On the basis of the plotted curve, sketch a polar cam mechanism that could be used for providing velocity loss, in terms of equivalent rounds fired, to a computer. Draw a schematic diagram showing how the cam output can be combined with initial velocity to produce an adjusted initial velocity value that can be used in the calculations performed by the computer.

3. On the graph plotted in problem 1, draw a straight line through the points (VL = 0, ESR = 100) and (VL = 140, ESR = 1500). The slope of this line is a constant K = 0.1. Read the difference in ordinate heights between the curve and straight line at intervals of ESR = 100. Using the same scales as in problem 2 and the same size base circle, plot a polar cam for the difference values. Compare the size and the contour of this cam with the cam obtained in problem 2. Draw a schematic diagram showing the cam, differentials, and gear ratio required to produce the adjusted value of initial velocity.

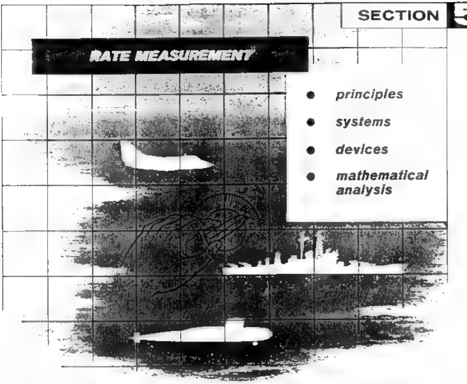
4. Shown to the right is a two bar linkage with bars of equal length K. The link for input A is constrained to move along the base line. At the zero position, the opening along the base line is equal to the lever length K so that the linkage forms an equilateral triangle. When an A input is applied, the output link is pulled downward through a distance B. Refer to the geometric diagram and write the equation for output B in terms of K and A. Note the relative complexity of the function generated by this simple linkage. The same function could be produced by cutting a cam, but a cam to produce equally accurate results might be considerably more expensive than the linkage mechanism.



SECTION 5

RATE MEASUREMENT

- *principles*
- *systems*
- *devices*
- *mathematical analysis*



This section will aquaint the student with various means available for measuring rates. Rate measurement is a necessary part of fire control operations, and the mechanisms which aid in such measurement are basic devices in computers. The type of rate with which we will be most concerned is speed of a vehicle: target speed, or own ship speed. Although other types of rate measurement will be discussed, they are to be regarded only as background to our particular interest in rates of vehicles. Measurement of displacement will also be discussed; however, it is to be considered only as part of the broader task of rate measurement. Rate measurement will be analyzed as a system or method of going about a task. In the first part of the lesson, the mathematics involved will not be specified, but after the mechanisms are understood in relation to their physical function, they can be clearly seen to perform mathematical operations. Therefore, the mathematics will be discussed at the end of the lesson.

scope of section

Basic principles of rate measurement will first be discussed. Then these principles will be seen as parts of possible systems of rate measurement. From this broad background the student will be shown particular mechanisms used in the systems. After the place of the mechanism in the system has been established, the mechanism will be examined as a mathematical device.

Rates may be measured in many ways. For instance, the speed of an aircraft can be measured by clocking it over a known distance, or by direct observation of the airspeed indicator. The methods used depend upon the situation, and the types of vehicles under consideration. The speed of a friendly aircraft could be obtained by radioing the pilot and asking him for a speed reading. If the aircraft were enemy, however, a different means would have to be used.

MEASURING SPEED

DIRECT MEASUREMENT

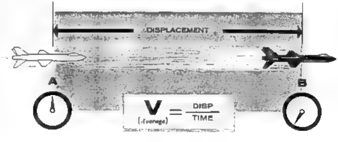
The direct application is used to find the speed of an object which is accessible to the observer. In order to measure rates directly, the observer must attach his measuring device to the object under investigation. Any speed measuring device, when used directly, will be in contact, in some manner, with that object.

DIRECT CLOCKING

Direct clocking involves either measurement of the distance covered by an object in a known time, or the time the object takes to cover a known distance.

Distance covered by an accessible object can be measured linearly in feet, yards or miles, using standard distance measuring devices, or rotationally in revolutions, degrees or radians, using dials or counters.

The speed of a moving object is usually expressed in feet per second, miles per hour, revolutions per minute, etc. These units have one common feature—they all represent units of Displacement per unit of Time. The clocking method determines velocity by finding displacement and dividing by the time taken for the displacement to be accomplished.



AVERAGE VELOCITY DEPENDS ON DISPLACEMENT AND TIME

The velocity given by this method is the average velocity over the time taken. In some cases we may wish to determine the instantaneous velocity.

The shorter the time interval between A and B in the diagram, the closer the average velocity would be to the instantaneous velocity of B. If we desired to determine the instantaneous velocity of the aircraft at point B, we would have to take an infinitely small time interval.

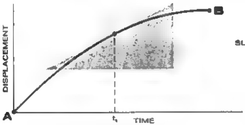
direct and indirect measurement of speed

The methods for finding rates can be applied in either of two ways—directly or indirectly. The direct application is used for an object in the immediate vicinity of, and accessible to, the observer. The indirect application is used for finding the speed of an unapproachable object, such as an enemy aircraft. We will now investigate a number of ways to measure speed. First we will apply them directly, and then apply them indirectly.

DIRECTLY

······REQUIRES CONTACT

One way to approximate an instantaneous rate is as follows: Instead of performing an arithmetical division, find the speed graphically by plotting on a graph the observed displacement vs. time.



$$\text{SLOPE} = \frac{\text{DISP}}{\text{TIME}} = \mathbf{V}_{inst.}$$

INSTANTANEOUS VELOCITY *EQUALS*

THE SLOPE OF THE DISPLACEMENT—TIME CURVE

The slope of the graph at any point, for example t_1, is equal to the velocity at that point. This method can be used to find instantaneous speed by taking the slope at point B. But, since B is the last point on the graph, the slope is difficult to determine accurately. A method using this principle was extensively used in fire control, but is now becoming obsolete.

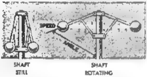
DIRECT SPEED SENSITIVE DEVICE

The speed sensitive device depends upon a physical quantity which is proportional to the speed of the object.

The pressure on the wing of an aircraft is proportional to its speed through the air.

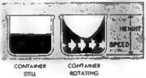
The temperature on the wing of an aircraft is also proportional to its speed through the air.

In a governor, the angle of the weighted arms is proportional to the rotational speed



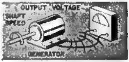
ANGLE proportional to SPEED

If a container of liquid is rotated, the height of the liquid is proportional to the rotational speed.



HEIGHT proportional to SPEED

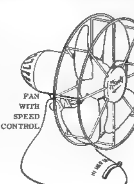
An electric generator produces a voltage proportional to the speed of its shaft



VOLTAGE proportional to SPEED

DIRECT CALIBRATED SPEED CONTROL

In certain cases, the speed of an object is porportional to the amount of power supplied to that object. For instance, the speed control of an electric fan or mixer determines the amount of power supplied to the motor. When the control is set at "high", the power supplied to the motor increases, and the speed of the fan increases in proportion. If the speed (high, medium, or low) of the fan is unknown, it may be determined merely by looking at the control setting.



The control knob need not have just four distinct settings. It may turn over a whole range of values. In the operation of an electric fan, it may not be necessary to have more than three speeds, but often speed must be changed gradually over a range of values. In such cases, the control dial may be calibrated to read any value of speed.

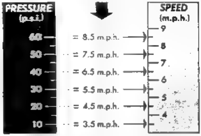
calibrating a scale

These physical quantities increase as speed increases, and decrease as speed decreases. When it has been determined exactly what value of speed corresponds to each value of the physical property, the scale measuring the property can be made to read in units of speed. This process of determining scale values is called calibration.

Suppose we had a pressure gauge with a scale as shown.

Then, by independent experiment, if we found the following correspondence:

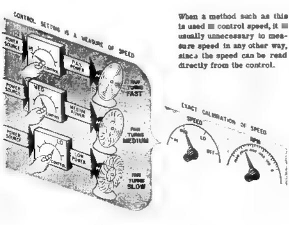
We could change the scale to read in miles per hour.



Now the scale is calibrated to read in m.p.h., whereas previously it had been calibrated to read in p.s.i.

note

In the clocking method, before finding speed we found displacement. Then we used the measured displacement to calculate speed. In the speed sensitive device, speed is measured directly. We need not find displacement in order to calculate speed. Therefore, we can know the speed without knowing the displacement. In order to find displacement when using a speed sensitive device, we must make an independent measurement. In the clocking method, displacement is a natural output, and no such independent measurement is necessary.



When a method such as this is used to control speed, it is usually unnecessary to measure speed in any other way, since the speed can be read directly from the control.

NOTE:

There are some specialized methods for measuring speed other than the three discussed here. One is by the Doppler effect which depends upon the fact that the frequency of waves changes with the relative velocities of the transmitting and receiving objects. The Doppler principle is used in aircraft navigation. Similar specialized methods are used in astronomy, but generally speed measurement will be confined to the three methods considered in this section.

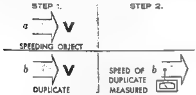
For purposes of simplicity, the following symbol will be used to represent direct measurement of the speed of an object.

MEASURING SPEED

The direct way of measuring speed required that there be contact between the speeding object and the observer. The indirect way is a means of avoiding this restriction. In fire control it is important to be able to measure rates indirectly, since direct contact with the target is usually impossible. When measuring speed indirectly, the speed of one object is used to determine the speed of another. A duplicate of the unavailable object is created, and the speed of the duplicate is measured. The duplicate must be an object whose speed can be measured directly. Thus, for indirect measurement, two requirements must be met.

1. CREATE A DUPLICATE OF A SPEEDING OBJECT.

2. MEASURE THE SPEED OF THE DUPLICATE.



duplicating speed (following)

Example FINDING THE SPEED OF AN AIRCRAFT

observer in aircraft B ············· FOLLOWS ············· aircraft A WHOSE SPEED CANNOT BE DIRECTLY OBSERVED

SPEED OF B DIFFERS FROM A

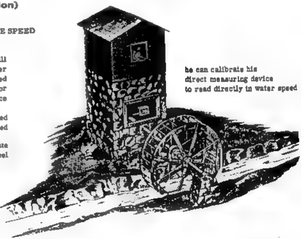
duplicating tangential speed (rotation)

Example A MILLER WANTS TO KNOW THE SPEED OF WATER IN HIS STREAM

. . . . . unable to leave the mill
he cannot clock an object in water
or find water speed
by immersing a pressure gauge or
other speed sensitive device

an indirect way must be used
to measure speed

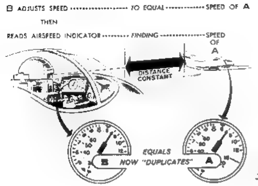
an available duplicate
is the water wheel



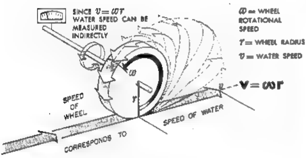
he can calibrate his
direct measuring device
to read directly in water speed

the wheel shaft which extends
into the mill, allows him
to use direct measurement
to find speed of the wheel

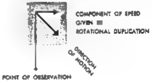
INDIRECTLY



SPEED OF AN AUTOMOBILE CAN [illegible] MEASURED IN THE SAME MANNER



Note that the speed given by this means of measurement [illegible] always perpendicular to the radius of the wheel, that is, tangential. Even if the object is moving in another direction only the tangential component will be measured.



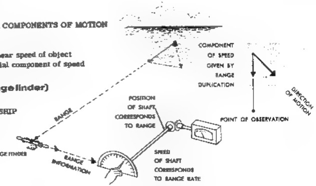
DUPLICATION CAN EXTEND TO OTHER COMPONENTS OF MOTION

Previous Examples Showed:

(jet plane and car) duplication [illegible] linear speed of object
(water wheel) duplication of tangential component of speed

duplicating radial speed (rangefinder)

Example THE RANGE OF AN ENEMY SHIP IS BEING CONTINUOUSLY MEASURED AND SUPPLIED TO A SHAFT



INDIRECT CLOCKING

DIRECT CLOCKING REQUIRES MEASUREMENT OF DISPLACEMENT OF THE OBJECT.

INDIRECT CLOCKING IS ACCOMPLISHED BY MEASURING THE DISPLACEMENT OF A DUPLICATE PROPORTIONAL TO THE DISPLACEMENT OF THE OBJECT.

For instance, in fire control, although we cannot measure the actual displacement of the target by means of a yardstick or tape, we can use the change in position of a point of light on a radar or sonar screen to determine the speed of the target. The only information we need is the relationship between actual distances and the distances shown on the screen.

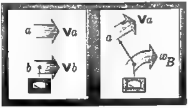
As in the case of direct measurement

DISPLACEMENT CAN BE PLOTTED AGAINST TIME.

SPEED IS DETERMINED BY THE SLOPE OF THE CURVE.

INDIRECT SPEED SENSITIVE DEVICE

Any method of measuring the speed of an object by using a speed sensitive device to measure the speed of the duplicate falls in this category. The two basic types of reproduction (linear and angular) both need only a speedometer to make them complete systems.



TO MEASURE SPEED OF A TARGET whose speed cannot be measured directly

CLOCKING OR FOLLOWING TAKE TOO LONG

FASTER METHOD IS TO

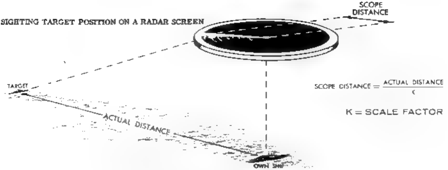
INDIRECT CALIBRATED SPEED CONTROL

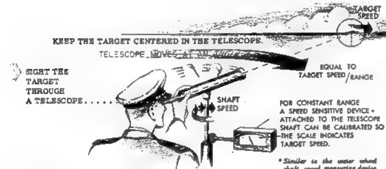
The indirect calibrated speed control is similar to its corresponding direct method except that,

IN THIS CASE,
THE DUPLICATE (NOT THE OBJECT ITSELF) IS CONTROLLED . . .

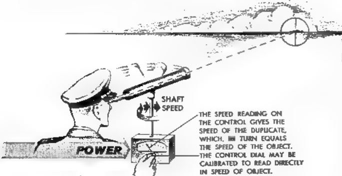
As an example, consider the telescope used for tracking with a speed sensitive device. In that case, the telescope was turned by hand.

Now let us assume that the telescope is driven by





Of course this is an extreme simplification, and factors such as changing range and course are ignored. Basically, however, this duplicate system is still the predominant one used to find target speeds.



The operator adjusts the angular speed of the telescope by turning the control knob.

review of principles

The three basic methods of measuring speed are:

1. CLOCKING
2. SPEED SENSITIVE DEVICE
3. CALIBRATED SPEED CONTROL

These methods can be applied directly or indirectly. When they are applied directly, they require direct contact between the object and the observer. When applied indirectly, they are attached to a device which is moving at a speed proportional to the speed of the distant object.

principles applied to systems

In each situation where speed measuring devices are used, the following four factors must be considered:

COMPONENT TO BE MEASURED

DIRECT OR INDIRECT MEASUREMENT

TYPE OF DUPLICATION

MEASUREMENT OF DUPLICATE

component to be measured

Do we want to measure the linear target speed, or a component such as the tangential velocity or range rate?

If one component is needed and another is easily measured, it may be possible to measure the easier rate and convert to the desired one by independent means.

direct or indirect measurement

Direct measurement is usually preferable to indirect measurement. Can we measure the rate directly? This will not be possible unless the observer is located on the object itself, or the object is a device such as a turning shaft.

type of duplication

If an indirect method is used, what will be the best way to duplicate target motion?

measurement of duplicate

Once we have the object or a proper duplicate, what method will we use for speed measurement?

a. CLOCKING
b. SPEED SENSITIVE DEVICE
c. CALIBRATED SPEED CONTROL

The method used depends upon prevailing conditions. The calibrated speed control is most important in naval fire control and, because of several unusual properties, will be considered further in detail. The other methods are largely self explanatory, and will be considered only briefly.

When the above four factors have been considered and the appropriate method selected, the outline of the system is complete. The specific equipment needed for each system remains to be discussed.

devices

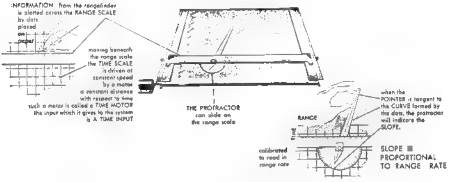
used in systems

CLOCKING DEVICES

The clocking method requires that there be
A MEASURE OF DISPLACEMENT
A MEASURE OF TIME
and
A WAY OF DIVIDING DISPLACEMENT BY TIME

It has been previously mentioned that
a graph may be drawn of displacement vs time.
The slope of that graph is the division DISPLACEMENT/TIME at any instant.
It represents an instantaneous velocity.

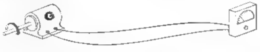
A device which performs this operation is
A GRAPHICAL RANGEKEEPER



SPEED SENSITIVE DEVICES

Most speedometers are speed sensitive devices.
The most common is
THE ELECTRICAL GENERATOR

The requirement for a speed sensitive device is that it have an output of a physical property proportional to speed. This physical property of an electrical generator is its voltage.



The input shaft speed determines the speed with which the armature windings cut the flux

The faster the speed, the more voltage is generated

A VOLTMETER can be calibrated to read directly in shaft r.p.m.

other speed sensitive devices

Other speed sensitive devices are aircraft air speed indicators which respond to the dynamic and static pressure of the air; governors, whose weights swing outward in response to increasing shaft speed, and types of gyroscopes which exert forces proportional to their speed. Applying the principle of a physical quantity proportional to speed, the student will be able to think of many such devices.

MEASURING SPEED INDIRECTLY

CALIBRATED SPEED CONTROL DEVICES

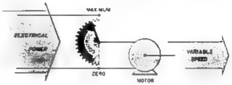
The two requirements for the calibrated speed control:

It must be able to control the power supplied to the object so that the speed of the object will be changed by turning the control knob.

It must be capable of measuring the speed of the object by the reading on the control dial.

calibrated electrical speed control

An electric motor with a potentiometer control which will supply a varying amount of power will meet the requirements.



calibrated mechanical speed control

The power input to the mechanical speed control is a shaft turning at constant speed. The output is a shaft whose speed varies according to the setting of the control.

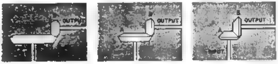
Consider one of a pair of beveled gears as an input, and the other gear as an output. Notice what happens when the size of the constant speed input gear is changed, while the output gear remains at the same size.

The speed control works on the principle of a constantly varying gear ratio. When the gear is changed, the speed of the output changes.

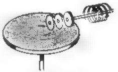
RATIO = 1:3 — SPEED OF B = 3 x A

RATIO = 1:2 — SPEED OF B = 2 x A

RATIO = 1:1 — SPEED OF B = A



The above gear ratio cannot be changed except by the clumsy device of changing gears. Even then, only three distinct output speeds are obtained. In order to vary the gear ratio continuously, the separate sets of gears can be replaced with a wheel rolling on a rotating disk.



The disk corresponds to the constant speed input gear.

The wheel corresponds to the variable speed output gear.

note

When wheel passes center of disk, its direction of rotation is reversed.

THIS FUNCTION CAN BE ACCOMPLISHED ELECTRICALLY AND MECHANICALLY

The potentiometer control will give low motor speed when it is near its zero position, and high motor speed when turned to its maximum position. ■ can be varied through the whole range of values between.

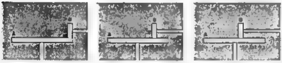
The dial on the potentiometer may be calibrated to read directly in motor speed. The correct speed for each dial setting may be found through independent experiment with other speed measuring devices, or by calculating the exact electrical relationships between the parts.

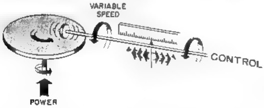
When the wheel moves toward the center of the disk, the gear ratio decreases, and the wheel turns slower. When ■ moves out toward the edge, the gear ratio increases, and the wheel turns faster. We now have the essential elements of a speed control device.

RATIO = 1:3 — SPEED OF B = 3 x A

RATIO = 1:2 — SPEED OF B = 2 x A

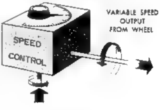
RATIO = 1:1 — SPEED OF B = A





Inward and outward movement of the wheel changes the speed of the wheel output.

The movement can be measured and calibrated.



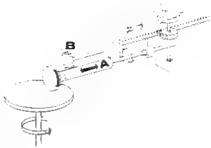
The mechanical speed control ■ an important and versatile device used extensively in computers. It will be worthwhile to investigate its properties further.

mechanical calibrated speed control

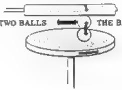
DISK AND WHEEL

HERE IS ONE WAY
TO CONSTRUCT THE VARIABLE GEAR RATIO

The presence of spur gear A permits the operator to move the wheel back and forth across the face of the disk, taking the output from gear B. Rotation of gear B is equal to that of gear A, but gear B does not move laterally across the disk. It is more convenient for instrumentation and connection to other mechanisms to take an output from a shaft which is stationary along its axis, such as that of gear B, rather than one which is moved axially, such as that of gear A.



BALL AND ROLLER

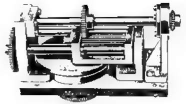


SCHEMATIC OF MECHANICAL SPEED CHANGER

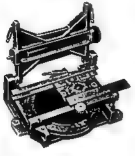
Consider the speed control now as part of a computer. In a typical computer, the values are carried from one mechanism to another by means of shafts. Each shaft has a value corresponding to its position. For instance, the differential adds because the angular position of the output shaft equals the sum of the angular positions of the input shafts. If all computer shafts had dials, these values could be read. Therefore, the value which the shaft carries in the computer depends only upon the position of the shaft.

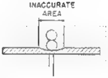
Similarly, when considered as part of a computer, the speed control shafts have values corresponding to their positions. When used in the indirect method, the output shaft of the speed control is a duplicate of the target. Its position and speed are proportional to target displacement and bearing rate, respectively. In a computer, however, only shaft position is important. Therefore, this output shaft is considered to give the displacement of the target. The speed control knob has a position corresponding to target bearing rate. The dial may be calibrated to read in terms of this rate. Since the value which a shaft has in a computer corresponds to its position, the output shaft represents displacement, and the rate control knob represents rate.

A SPEED CONTROL, CONSTRUCTED IN THIS WAY, IS IN ACTUAL USE

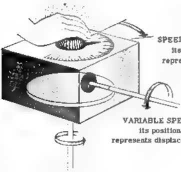


A BALL AND ROLLER TYPE SPEED CONTROL
(with the (roller) plate lifted)

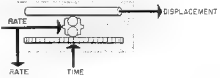




note
As the disk turns, with the balls in their zero position in the center of the disk, a small depression will eventually be worn in the disk by the pressure of the balls. Therefore, inaccurate readings will result in an area around the center of the disk. The computer should be designed so that significant outputs are not taken from this section of the disk.



The speed changer is symbolized below



The time input is the constant speed power input. The shaft, since it is rotating at constant speed, can be considered as a time motor, just as the constant speed motor moving the graphical rangekeeper represented time.

MATHEMATICAL REPRESENTATION

The mathematical principles related to speed measurement are the same as the mathematical principles related to speed.

As we have seen, it is possible to understand the basic function of speed measurement without using detailed mathematics. However, a few mathematical principles are important in order to fully understand the devices covered.

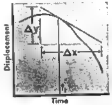
Speed is a rate, and the mathematics which deals with rates is calculus. The specific relationship between speed, displacement and time is

$$s = \frac{dl}{dt}$$

l = displacement
s = speed
t = time

where s is the instantaneous speed at any time (t).

The expression reads: speed equals the derivative of displacement with respect to time. This is the process of differentiation. Any mechanism which measures speed, then, in a sense, can be called a differentiator, but particularly those devices which use displacement and time in order to determine speed.



Slope = Speed at t_1

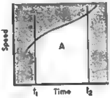
$$= \frac{\Delta y}{\Delta x} = \frac{dl}{dt}$$

MATHEMATICAL REPRESENTATION

In calculus, the reverse of the process of differentiation is integration. Using our properties of distance, rate, and time, integration may be expressed by

$$l = \int s dt$$

which states that displacement equals the integral of speed with respect to time.



Area = Distance Traveled from t_1 to t_2

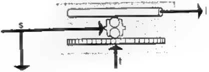
$$= \int_{t_1}^{t_2} s dt$$

a mechanical integrator

Now, notice the schematic of the calibrated speed control. Although it is principally used to determine speed, it also has an output of displacement. This output may be measured by a dial or counter. If it is considered to be the principal output, we could say that this device performs the integration.

$$l = \int s dt$$

where s and t are inputs, and l is the output. Thus, the speed control is called an integrator, because it can be used for integration, although its primary use is to measure speed.



analysis

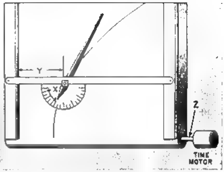
OF RATES

a mechanical differentiator

One device which uses displacement and time to determine speed is the graphical rangekeeper. It can be used to find the derivative of any function of the form

$$x = \frac{dy}{dz}$$

where y is substituted for range, z is substituted for constant speed, time motor input, and x is the slope of the curve, equivalent to range rate.



Graphical Rangekeeper as A DIFFERENTIATOR

OF DISPLACEMENT

GENERAL INTEGRATION

Just as the graphical rangekeeper used as a differentiator can find any derivative of the form

$$x = \frac{dy}{dz}$$

The speed control used as an integrator can find any integral of the form

$$y = \int x dz$$

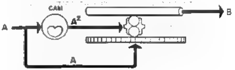
where y is substituted for displacement
x is substituted for speed
z is substituted for time motor input.

A PARTICULAR PROBLEM

Suppose it is required to mechanize the following integration:

$$B = \int A^2 dA$$

If A^2 is substituted for speed input, and A is substituted for time input, then B will be the output which was formerly displacement, and the schematic would look as follows:

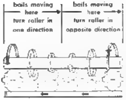


A Specific Integration

Therefore, the speed controller can be considered as an integrator.

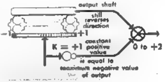
uniform positive output

In previous cases, the output shaft of the speed changer could turn in either direction.



roller reverses direction as balls move from one end of disk to the other.

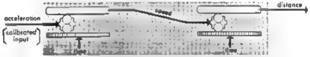
In certain instances, the input might always be positive. We would then want the output to be positive all the time. A constant positive value may be added to the output. When the output is at its maximum negative position, the constant positive value balances this negative value, and their sum is zero. As the output becomes less negative, the sum will increase from zero, always remaining positive.



sum of two values is always in one direction

measurement of acceleration

The integrator has been shown to measure speed. It can also be used to measure acceleration. Acceleration is measured by the use of two integrators.



speed = $\int$ acceleration x time

$$s = \int_{t_1}^{t_2} a\,dt$$

distance = $\int$ speed x time

$$l = \int_{t_1}^{t_2} s\,dt$$

PROBLEMS

1. Name three built-in devices which can measure the speed of an object, and show what characteristic of these devices enables us to measure speed; e.g., generator — output voltage proportional to speed.

2. Draw a schematic of a computer to solve the problem:

$$E = A/B + \int C dt + \frac{1}{D} - KA$$

Inputs: A
B
C
D
dt = time input as supplied by a constant speed motor
K = constant

3. How would it be possible to find the speed of an automobile by means of a calibrated input? (Assume direct contact with the automobile is possible, and that you are the driver.)

SECTION 6

AUXILIARY DEVICES

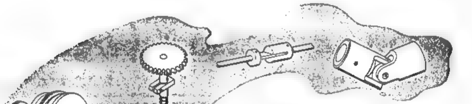
used in computers

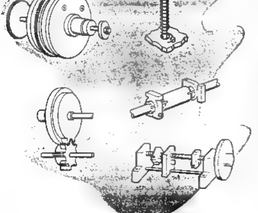
INTRODUCTION

Previous lessons covered the various mechanisms that are employed in computers. There are additional auxiliary devices which, while they perform functions that are not directly involved in computations, play important and sometimes essential roles in the operation of a computer. While emphasis will be placed on devices used in mechanical computers, many of them have counterparts in electrical computers and are found in other equipment as well.

Among the auxiliary devices commonly found in mechanical computers, are the following, formed into related groups:

- LIMIT STOPS AND SWITCHES
- COUPLINGS AND UNIVERSAL JOINTS
- CLUTCHES
- FRICTION DEVICES
- INTERMITTENT DRIVES
- ADJUSTMENT DEVICES
- LOST MOTION TAKE-UP DEVICES
- DETENTS
- REGULATING DEVICES





PURPOSE

Each item in a specific group has a particular purpose and function. For example, an intermittent drive is used to disconnect the input in a computer when the input is not within the range of operation. A limit stop may control either the maximum forward movement of a carriage or the maximum rotation of a shaft. A friction relief drive will prevent a gear from being overloaded and protect it and associated parts from damage. The take-up spring may be used to keep gear teeth in close mesh, thereby saving lost motion and improving accuracy. Each auxiliary may do a similar job in the operation of other equipment.

The devices mentioned here do not comprise a complete list of the auxiliary components. Servos, synchros, and data presentation devices are covered in other lessons, with the detailed treatment they necessitate.

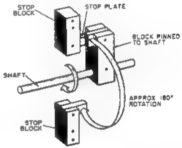
LIMIT STOPS AND SWITCHES

the limit stop

A limit stop is a device for preventing movement of a machine part beyond a set limit or limiting movement within a set of limits.

SIMPLE LIMIT STOP

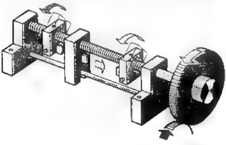
By using two blocks as fixed stops and pinning a third block to a shaft, shaft travel would be limited to movement between the two stops, like this:

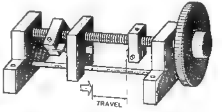


TRAVELING NUT LIMIT STOP

This type of limit stop is used where more than one shaft revolution is involved. A gear, driven by the mechanism it is to control, is mounted on the end of a threaded shaft. A traveling nut riding the shaft is prevented from rotating by a guide rod. Shaft rotation causes the nut to move back and forth, direction of nut travel depending upon shaft rotation.

A pair of adjusting nuts, one on each side of the traveling nut, are secured to the shaft in the desired positions by set screws or clamps. When a stop of the traveling nut strikes the stop of an adjusting nut the shaft is prevented from further rotation since this is the extreme limit of travel in that direction.

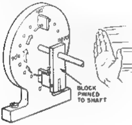


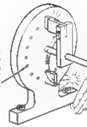


The span between adjusting nuts may be set to provide the exact number of shaft revolutions desired. Changing gear ratios would also do this, having the effect of shortening or lengthening the run between limit stops as compared to machine operation.

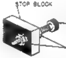
ADJUSTABLE STOP

A series of holes in a plate or in rim of a gear would permit the stop blocks or stop pins to be changed at will to provide a specified degree of shaft rotation.



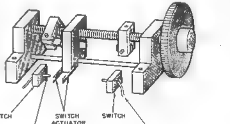


We could add a refinement by putting adjusting screws in the stop blocks. Such screws could be set and locked in place to provide travel within finer limits, or used to set the range slightly one way or the other.



LIMIT SWITCHES

The electric switch is a familiar item to us. We know that it is a type of mechanism used to turn electric power on and off, or to switch electric current from one circuit to another. It would be a simple matter to fasten a couple of contactor arms on the traveling nut of a limit stop unit and to mount a pair of on-off electric switches to be actuated when contacted by the blades. The electric switches could be set to control the operation of the mechanism between the prescribed limits, and the mechanical stops set somewhat beyond them. Normal operation would be within the limits of the electric switches. In the event of a defective switch, short circuit, or other reasons which would allow the mechanism to run beyond the electric switch limits, the mechanical stops would be brought into play as a safety or protective feature.



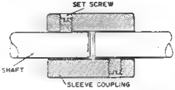
COUPLINGS AND UNIVERSAL JOINTS

couplings

The broad term "coupling" applies to any device that secures two parts together. Line shafts made up of several lengths of shafting may be held together by shaft couplings. There are several types of shaft couplings. We will check on a few of those commonly encountered.

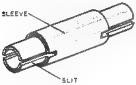
PLAIN SLEEVE COUPLING

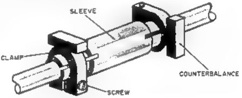
The plain coupling consists of a sleeve which receives the ends of the two shafts it is to join, and is secured by set screws or pins so the assembly can turn as one.



CLAMP TYPE SLEEVE COUPLING

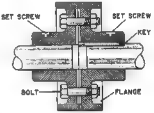
Used to join two closely aligned shafts. It also offers an adjustment in shaft relationship. This coupling consists of a sleeve, the ends of which are slit so clamps can be applied to hold the two shafts firmly together in the sleeve and turn as one.





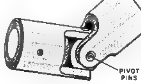
FLANGE COUPLING

The flange coupling finds use on shafts which tend to be pulled apart in operation. A pair of flanges, secured to the ends of the shafts by set screws, are pulled together by bolts and nuts. Splines or keys are resorted to in the case of heavy duty drives.



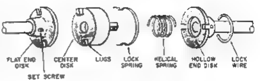
universal joints

A universal joint is a shaft coupling which allows shaft movement in any direction within a limited angle and conveys a positive motion to the driven shaft. Many universal joints will function with shafts up to 45 degrees out of alignment.



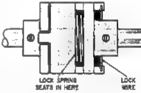
OLDHAM COUPLING

The important feature of the Oldham coupling is that it can be readily connected or disconnected. It is used to join shafts that do not require perfect alignment. Because of its spring loading it also finds use as an expansion joint in long shafts. The Oldham coupling consists of a pair of disks, one flat and the other hollow, pinned to the ends of the shafts. A third disk, with a pair of lugs projecting from each face, fits between the two shaft disks. The lugs fit into slots of the two end disks, and enable one shaft to drive through the disks to the other shaft.



EXPLODED VIEW OF OLDHAM COUPLING

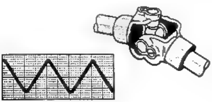
A helical spring, housed within the center and hollow end disks, forces the center disk against the flat disk. With the coupling assembled on the shaft ends, a flat lock spring is slipped into the space about the helical spring. The ends of this flat spring are formed so that when it is pushed into place the ends spring out and lock about the lugs. A lock wire is passed between holes drilled through the projecting lugs to guard the assembly. It is a simple matter to remove the lock wire, withdraw the lock spring, compress the helical spring by pushing and sliding back the center disk, and disconnecting the shafts. Reinstallation requires no measuring or setting as the assembly fits quickly and smoothly into place.



OLDHAM COUPLING ASSEMBLED

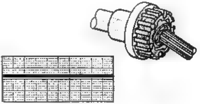
CROSS PIN UNIVERSAL JOINT

The universal joint is widely used although the joint changes velocity of the driven shaft with two high points and two low points each complete revolution. This fluctuating velocity induces similar torque variance, causing vibration and wear throughout the associated mechanism. Because of the two pins, one shaft can drive another even though the angle between the two is as great as 25 degrees.



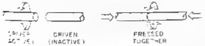
CONSTANT VELOCITY UNIVERSAL JOINT

A new development in universal joint design provides smooth torque even at unbalanced angles, resulting from ball bearings applying power in a plane that bisects both shaft axes. The torque developed is shown in the graph.



CLUTCHES

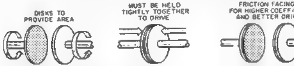
A motor often drives more than one line of shafting, and situations arise in which one or another of the lines must be stopped without stopping the other lines. A simple solution would be to have a severed shaft. To drive, the ends would have to be pressed together so that frictional force would enable the shafts to rotate together.



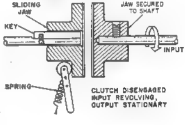
However, since the surface area of the two ends is small, the torque transmitted is also relatively small. Torque is a function of: (1) the force with which the cutting ends are held together, (2) the surface area, and (3) the function characteristics of the material involved.

DISK DRIVE

By attaching disks to the shaft ends, the surface contact area is increased, thus increasing torque. Further increases can be brought about by using a material with a high coefficient of friction on the contacting surfaces.

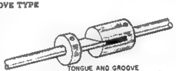


Such disks require they be thrust firmly together to drive without slipping. Pinning a key to one shaft and slotting its disk to permit it to slide longitudinally on shaft and key would provide a quick means of engagement or disengagement. By using a simple lever (refined perhaps by adding a roller and spring to hold the disk under tension in the selected position), the sliding disk could be moved to disengage it or be forced into good driving contact with the other disk. Each line of shafting so equipped could be engaged or disengaged as desired, without interfering with the other lines. This type of clutch may be used at very high speeds, although it is subject to slippage.



TONGUE AND GROOVE TYPE

Another clutch of simple design, used to a great extent in small equipments, is the so-called tongue and groove clutch. Its simplest form involves cutting a slot or groove in the end of one shaft and cutting away the end of the other shaft to provide a mating or infitting tongue. Since this would weaken the shaft ends, a machine or die cast assembly is pinned to the shaft ends, like this:



TONGUE AND GROOVE
(TONGUE JUST ENTERING GROOVE)

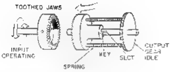
If a groove is cut in one of the sections so a yoke or fork can be used to move it in or out of engagement, a simple positive-acting clutch is had. The connection is a positive, or locking, one that can be relied upon for accuracy since there is no slippage. A major disadvantage is engagement at other than low speeds. At medium speeds engagement would not be immediate or smooth, while at high speeds connection may be impossible. The tongue and groove assembly is also used as a coupling, since it offers an easy means of removing shaft sections. By leaving a slight space between the two engaged sections, compensation for shaft expansion is had.

TOOTHED JAW CLUTCH

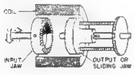
With toothed or serrated jaws, engagement can be achieved rapidly without exact shaft position alignment, at high speed, and with heavy loads. It is a locking type of clutch permitting no slippage. Revolutions of the output side will equal those on the input side. Some means are needed to control jaw movement for engagement or disengagement and, when coupled, exert force necessary to keep the jaws together. A simple toothed jaw clutch would look something like this:

By keeping one jaw slidable on the shaft and providing a yoke, we would have a manually controlled mechanical means of engaging or disengaging the clutch.

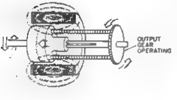
THE SOLENOID CLUTCH



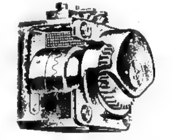
The solenoid offers the electrical means of connecting or disconnecting a drive. The solenoid clutch is comprised of two cylindrical jaws with serrated mating edges within a solenoid coil. One jaw is secured to the input drive shaft and revolves with it. The other jaw is mounted on a hub and made so it is slidable longitudinally on the shaft, moving on a key or in a slotted section.



A spring (or springs) keeps the jaws apart and out of engagement when the solenoid is not energized. Energizing the solenoid magnetizes both jaws, and the slidable output jaw is pulled into contact with the input jaw. As long as electric current is supplied to the solenoid, the magnetic field is maintained and the jaws are held in engagement. Power is transmitted through the clutch to the output shaft without slippage. When electric current is turned off, the magnetic field ceases and the springs withdraw the sliding jaw. With application or cessation of electric current, jaw reaction is almost instantaneous. This rapid, certain clutch connect or disconnect action makes the solenoid clutch a favored means of control in high-speed equipment.



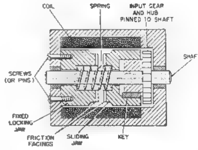
CUTAWAY VIEW OF SOLENOID CLUTCH



THE SOLENOID LOCK

A solenoid lock works like the solenoid clutch, except one jaw is pinned to the housing. The other jaw is slideably keyed to the hub of the input gear, free to turn as long as the solenoid coil remains deenergized. The gear is the input in this assembly.

Energizing the coil draws the sliding jaw along the gear hub, locking it to the pinned jaw and preventing any further motion of the input gear or its associated parts. This device is used where a quick-acting lock is required to stop the equipment and hold it immobile as long as current is applied to the coil.



The solenoid lock is often used in conjunction with a solenoid clutch. When the clutch disengages, the solenoid lock is brought into play (by means of electric switching circuitry) locking that part of the mechanical equipment in its exact disengaged position.

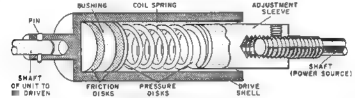
FRICTION DEVICES

SAFETY FRICTION DRIVE

When it is desirable to provide a driving means that incorporates a safety feature, the safety friction drive may be used.

The mechanism drive shaft is secured to the drive shell. Inside the shell is a friction disk (or disks), and a coil spring, spaced between pressure disks, which provides the required thrust against the friction disks. An adjustable sleeve, placed on the power source drive shaft, is secured by set screws or a clamp. By moving the sleeve or clamp, the spring pressure can be adjusted for greater or lesser loads.

Drives are adjusted to carry the load, plus a slight overload, without slippage. When the load increases beyond this point, it overcomes the friction, and the drive will slip, thus preventing damage to the gearing or mechanism in that particular unit.



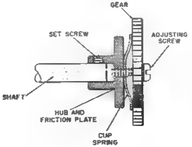
SAFETY FRICTION DRIVE

FRICTION RELIEF DEVICE

The function of the friction relief device is to prevent shock and undue strain on gearing, shafting, and mechanisms. For example, where a sudden stop is produced by a limit stop, or a reversal of shaft rotation takes place, the friction relief would slip and prevent damage. Under normal load it might be said to be inert, for it remains inactive, carrying the load without slippage. When overloading occurs, it slips until the load is returned to normal.

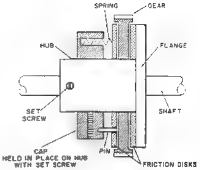
SIMPLE FRICTION RELIEF TYPE

A simple unit, suitable for very light work, may consist of a flanged hub pinned to the end of a shaft. A gear, rotatable on a screw, bears against a cup spring which in turn bears against the flange. Manipulation of the screw adjusts the cup spring tension. By turning this screw just a trifle more beyond the point when friction is sufficient to carry the normal load, a friction safety relief is had. Slippage will occur if an increase above normal load takes place.



ANOTHER FRICTION RELIEF DEVICE

This type is suitable for heavier duties. It is comprised of a flanged hub secured on a shaft by means of pins or set screws. A cap, pierced with a series of holes to provide pockets for springs and drive pins, slips over the hub and is secured to it with set screws. A pair of friction disks, one on each side of the drive gear, is placed under pressure by moving the cap toward the flange. By moving the cap to a new position on the hub, spring pressure can be adjusted. Adjustment is considered proper when the resistance offered by the friction disks against the flange gear faces permits the gear to drive at shaft speed without slipping at normal loads. If the load becomes abnormal, or if sudden stoppage occurs, the gear will slip between the friction disks, saving equipment from damage.

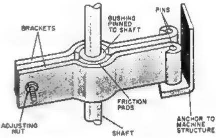


FRICTION HOLDING AND FRICTION RELIEF DEVICES

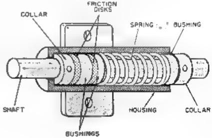
The action of friction holding and friction relief devices depends upon friction initiated by a spring or some resilient material upon a shaft, disk, bushing, flange, or some other intermediary between the moving and the associated surface.

SHAFT FRICTION HOLDING DEVICE

The simplest form of a friction holding device is a pair of brackets with friction pads bearing directly on the shaft. Where greater friction surface is desired, a bushing is pinned to the shaft. By mounting the brackets on hinge pins and using an adjusting nut, the degree of pressure can be controlled, adjusted, and varied to suit the needs of the job. For example, if prevention of oscillation is desired, a light friction might be used for this damping process. Slightly more pressure might be used to give more holding power when the shaft friction device is used to prevent mechanical feed back, which would change the shaft value. A holding friction is one that exerts a drag on a shaft so that a force greater than the drag on a shaft has to be used before the shaft can turn.



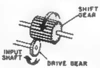
Another shaft friction holding device used to prevent oscillations and shaft values from backing up is comprised of a housing, bolted to some part of the equipment so it is held stationary, through which the shafting is run. By means of a spring exerting pressure on friction disks which "brake" against the bore of the housing, a degree of friction is set up which must be overcome before the shaft can turn. The holding friction developed by the friction disks depends upon the force applied to them by a helical spring. Spring pressure can be adjusted by moving the collar to a new position.



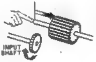
An intermittent drive is a mechanical arrangement which will automatically deliver power at definite intervals, or automatically and selectively engage or disengage mechanisms having different limits of operation and being driven from the same line of gearing. A device enables the output shaft to be locked upon disengagement from the drive, and held immobile until picked up later at the very same position at which it was cut out.

ELEMENTARY SHIFT

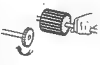
The simplest form of intermittent drive would be a hand-operated assembly. For example, to disengage input or reengage at a desired point, we could utilize a slidably mounted broad-faced gear between the input and output gears. With gears in mesh, power would be delivered to the output shaft.

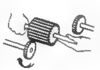


Pushing on the shaft of this broad-faced gear would serve to disengage the drive.

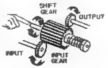


To lock the output in the particular position at disengagement, the shaft can be grasped with the hand, or locked with a clamp or wedge. In place of these crude methods, however, we can use a lever and cam assembly. Thus, power would be delivered to an output gear for a definite period, then stopped, and kept inactive for another definite period. The input would operate continuously. In certain mechanical equipment, such an assembly would be used to provide a regular rhythm of power application and idle time.





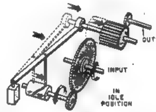
If we put a spring on the shaft, removal of the pressure would allow the gear to slide back into driving position.



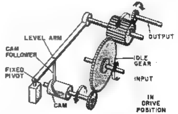
Intermittent drives have application in many mechanisms on computers, including multipliers, component solvers, and transmitters. Intermittent drives must be compact and accurate. Basic mechanisms comprising an intermittent drive are relatively simple devices. They consist of an intermittent gear: spider and planetary gearing; and a lever, cam and clutch shift, all of which are contained within a housing.

THE CAM AND LEVER SHIFT

A mechanism supplying a force which slides a lever arm in and out of position at certain points is required to provide automatic engagement and disengagement. As the motion of a shaft is rotational, a device is required for the conversion of rotational motion to linear motion. An assembly comprising a grooved cam, cam follower, lever, and a fixed pivot will provide the proper action. The cam, made by cutting a continuous groove around its wide perimeter, is mounted on a shaft. The groove is formed so that it sweeps in one end of the cam face one-quarter of the way, then swings to opposite end the rest of the way. A pin, put into this groove, would be moved back and forth linearly while the cam rotates. If the pin is fixed to a lever arm which, in turn, is mounted on a pivot, the reciprocating movement can be utilized to move the output gear in and out of drive, like this:



When the cam is rotated to the position that throws the gear out of engagement, output delivery will cease. Input will continue unchanged. By use of proper gearing and gearing ratios, a simple intermittent drive can be designed for specific active and inactive deliveries.

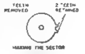


INTERMITTENT GEAR

The intermittent gear is the simplest and most compact means of obtaining a definite time of drive, an idle period, and, most important, an output locked in a fixed position ur : disengagement from the drive.

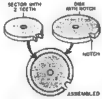
EVOLVING AN INTERMITTENT GEAR

If 18 teeth are removed from a 20-tooth gear, with 2 teeth remaining intact for driving, the driving value would be reduced to 2/20, or 0.1, thus leaving an 0.9 inactive value.

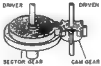


A multilated gear of this sort would not mesh properly in service.

To make an operable unit, a disk with the same periphery as the major diameter of the gear is required. Its edge is notched to permit entry of a tooth of the driven gear. The multilated gear and notched disk are fastened together to make a sector gear, like this:

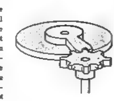


A gear with 8 teeth could be altered by cutting 4 alternate teeth down to one-half length. Such a driven gear, with 4 long and 4 short teeth, would engage the sector driven gear like this:



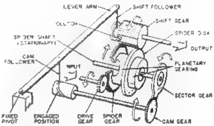
When these gears mate in transfer (active driving position), the 2 teeth on the sector engage and move one of the long teeth of the driven cam. The notch in the disk part of the sector allows this long tooth free passage and causes the sector gear to move one-quarter turn.

As the long tooth leaves the notch, its lower peripheral edge, as well as that on the next long tooth, bears against the disk edge. The driven gear is thus locked in position by the 2 long teeth, the short tooth riding on the disk face. A machined intermittent gear assembly might look like this:

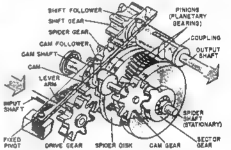


THE INTERMITTENT DRIVE UNIT

An examination of an intermittent drive unit would reveal the presence of a cam and lever shift, intermittent cam gear, spider and planetary reduction gearing, and of course, input and output shafts. A schematic sketch of the assembly may be presented this way:



Actually the assembly, with the housing removed, would look like this:



OPERATION OF INTERMITTENT DRIVE

The drive gear, pinned to the input shaft, drives the spider gear which, in turn, drives the shift gear.

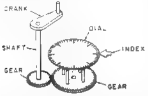
The disks and pinion gears on the spider shaft serve to reduce speed so that the 2-tooth sector gear will drive much more slowly than the spider gear. The 2-tooth sector gear drives the cam shaft gear very slowly. Cam action, by way of the cam follower, will move the lever arm. The shift follower at the end of the lever arm fits into a circular groove on the shift gear. Movement of the follower causes the shift gear to slide along its shaft. Sliding the gear in one direction takes the shift gear out of mesh with the spider. This is the way the intermittent "cuts out". The input can continue to turn, but, since the shift gear is not meshed, it remains stationary. The shift gear stays IN mesh for a certain number of revolutions of the drive shaft, then the cam action causes the shift follower to move the shift gear OUT of mesh.

The path of the groove forming the cam is such that for one-quarter of the distance around, the cam follower will put the shift gear into mesh with the spider gear. When the cam follower is in the other three-quarter section of the groove, the lever arm moves the shift gear out of mesh.

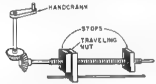
ADJUSTMENT

SIMPLE HANDCRANK

The simplest adjustment device is the handcrank mounted on a shaft, with a drive gear on the other end, like this:



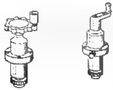
This handcrank could be used to set a dial or to run the traveling nut to each end of a limit stop to determine what the travel limits might be.



HANDCRANK UNITS

The handcranks on computers are usually just taken for granted as parts of the systems on which they are mounted. Actually they are important mechanisms, used to turn lines of gearing to feed inputs into various mechanisms, put values or correction factors into computers by hand, or provide means of operating the system in emergencies when normal automatic transmission fails.

Handcranks for computers are made up as units that can be screwed or bolted into position. Here are a couple of typical handcranks:

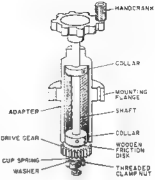


WHAT HANDCRANKS CAN DO

The handcrank may be a simple crank, shaft, gear, and adapter assembly which, as a unit, is screwed into or bolted to the computer. Various devices can be added to the simple handcrank to enable it to do other jobs, or even several jobs. For example, it may have:

1. Adjustable friction relief drive.
2. Adjustable holding friction.
3. Positioning plunger, to hold handle in a specific position.
4. Adjustable pushbutton switch-bolt.

DEVICES

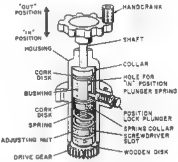


FRICTION RELIEF HANDCRANK

The handcrank can be provided with an adjustable friction drive, by using a cup spring (or a helical spring) to apply pressure upon a gear bearing against a wood or composition disk. Adjustment of a clamp nut provides the means of varying the pressure to obtain the degree of friction required. If pressure becomes greater than the friction imposed upon it, the gear will slip and protect associated gearing from strain or damage.

ADJUSTABLE HOLDING FRICTION

The same handcrank may be provided with cork disks, a collar, and a bushing. This assembly puts a drag on the handcrank, keeps it positioned, and prevents motion from backing out through the handcrank.

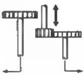


POSITIONING PLUNGER

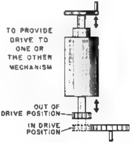
We can carry the design of the handcrank still further and add a plunger for the purpose of holding the shaft in either of two positions: an IN position and OUT position. In changing position, the shaft and the drive gear move in relation to the adapter housing. The plunger is pulled out and the handcrank pushed or pulled to its new position. When released, the plunger is returned by a spring and enters a hole in the bushing, locking the assembly in a particular position.

Moving the handcrank to the in or out position will cause it to engage or become disengaged, or this arrangement can be used to drive one or the other mechanism. By using a wide gear, this drive can be kept in engagement all the time, the in and out position being to control the drive of another gear. Thus, it is possible to drive one gear at all times, alone, or in conjunction with another. Further, we would include a switch actuated by the in or out position of the shaft.

TO DRIVE ONE GEAR AT ALL TIMES, ALONE, OR WITH ANOTHER



TO PROVIDE DRIVE TO ONE OR THE OTHER MECHANISM

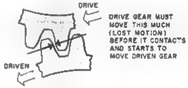


LOST MOTION

TAKE-UP SPRING

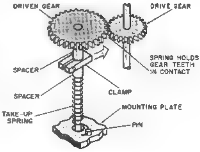
Take-up springs are used to prevent lost motion between pairs of meshing gears. If a pair of gears not equipped with a take-up spring is inspected when at rest, it will be observed that a certain amount of space exists between the engaged gear teeth. Rarely are load and drive conditions such that when the machine stops, will the gear teeth remain in contact like this:

Generally there is a space between the driving surfaces of the engaged gear teeth. When the driving gear begins to turn, the immediate tooth involved has to move through this clearance space before it contacts the tooth on the driven gear. This wasted motion is referred to as lost motion. Lost motion may result in considerable error in a gear train having a number of meshing gears.



A take-up spring will hold the engaged teeth firmly against each other, whether the shafts are turning or stationary.

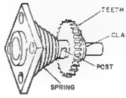
The usual form of take-up spring has one of its ends attached to a mounting plate or to the machine housing. The other end is attached to a clamp fixed on the shaft. The clamp is generally set in place between spacers, the latter pinned in place. The spacers prevent the clamp from being pulled along the shaft when the spring tension is being adjusted. Spring adjustment can be made by loosening the clamp screw and turning the clamp to wind or unwind the spring, depending upon whether an increase or decrease in spring tension is desired.



TAKE-UP DEVICES

TAKE-UP UNIT

A take-up unit that uses a flat or clock type of spring is used when a short shaft prohibits employment of the spiral take-up spring. In this unit one end of the spring is secured to the housing. The other end of the spring, pierced with a hole, is slipped over a pin on the cap of the unit. Spring adjustment can be accomplished by loosening the clamp and turning the cap to the desired position, reclamping to retain the particular tension.

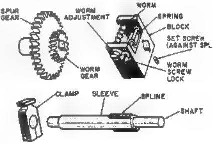


VERNIER GEAR CLAMP

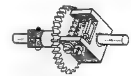
A vernier gear clamp is used to provide a fine adjustment for positioning a gear on a shaft. The vernier permits the gear to be turned very small amounts relative to its shaft.

VERNIER GEAR CLAMP CONSTRUCTION

The components of the vernier gear clamp are depicted individually. Assembly is accomplished by slipping the sleeve, with integral splines, on the shaft. The spur and worm wheel component fits on, and can turn on, the sleeve. The block is formed to fit the sleeve and its splines. One set screw (or more), bearing on the spline, holds the block securely on the sleeve. A clamp is used to secure the sleeve to the shaft.



We can secure an approximate or rough setting of the spur gear by loosening the clamp and revolving the assembly on the shaft to the initial position. The clamp is then tightened. Manipulation of the worm adjustment will very accurately position the spur gear relative to the shaft. The worm adjustment screw has a flange and, when proper setting is secured, is held in this position by the head of another screw called the worm screw lock. End-shake of the worm is eliminated by a bent washer spring under a collar on the end of the worm. This serves to hold the worm and worm gear in close mesh to eliminate lost motion and hold the accurate adjustment.



ASSEMBLED VERNIER GEAR CLAMP

Where fine control and accurate transmission are required, gear teeth are worked to very close dimensions, some being honed for precision. Even so, tiny discrepancies occur, plus the fact that a certain amount of clearance is required between gear teeth to permit meshing. A take-up device is used to overcome the clearance and lost motion in gearing.

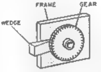
DETENTS

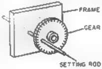
DETENTS

A detent is a device or means in a mechanical assembly for checking, holding, or releasing a movement at a predetermined exact position. A detent may be comprised of nothing more than a pin fitted through mated holes: a simple mechanical device, exemplified by a pawl and ratchet; or more complex mechanisms, such as the intermittent drive. Various detents of particular interest are presented in the following paragraphs.

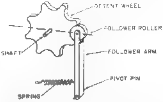
WEDGE. The simplest of all detents would be a wedge. For example, to hold an input shaft in position when checking or setting equipment, a wooden or bakelite wedge may be inserted between the gear and the frame. To avoid damage, a wedge must be inserted firmly enough to hold the shaft line, but should not be hammered in.

SETTING ROD. Another simple detent is the setting rod or pin on a computer. The rod is an accurately ground steel rod, fitted into two accurately sized holes, one through a gear and the other through the frame. With the holes in line and the setting rod inserted, the gear will be held in an exact position.





DENTATE DETENT WHEEL. A common form of detent used where a shaft is to be held firmly in any one of a multiplicity of exact positions, is one which has a specially designed detent wheel assembly, as shown:

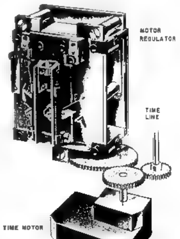


The important feature of the detent is that it permits the use of an accurate set of values, depending on the detent wheel design. These values or settings are those comprising the center line of hollows in the detent wheel. No values can be set at the peaks or other than dead centers of the hollows. This detent will pull the shaft to exact position if the roller is released near this position; drawing and holding the shaft to this desired position.

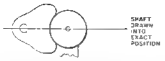
REGULATING DEVICES

THE MOTOR REGULATOR

Certain mechanisms are required to operate at a constant speed, independently of variations in load.

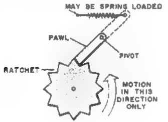


The illustration presents a motor regulator as it would appear connected to a time motor and time line.



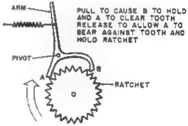
Turning the shaft by crank, for example, forces the roller out to the end of the tooth and into the next hollow. Further, if the next setting desired is several notches or hollows away, the operator would continue cranking until the desired hollow is reached. As soon as the roller begins to enter the hollow, the spring on the follower arm exerts sufficient force to bring the roller into exact position. Shaft may be operated in either direction.

THE RATCHET. The pawl and ratchet represent the simplest form of automatic detent. The ratchet is used to permit transmission of motion, intermittent or continuous in one direction, and as a holding means to prevent the ratchet wheel from rotating backward. This form is commonly used in connection with hoisting mechanisms or applications where it is essential the shaft is prevented from turning in the reverse direction under action of load or discontinuance of power.



When the ratchet is revolved in a direction where the tooth rises under the pawl, the pawl will be lifted and allow ratchet motion. The pawl drops back, due to weight or spring loading, and, bearing against the face of the ratchet tooth, prevents motion of the ratchet in the reverse direction. The ratchet may be spun rapidly, throwing the pawl out of action until the motion slows to permit the pawl to drop in between the teeth, engage, and prevent motion in reverse from that point.

ESCAPEMENT RATCHET. A refined version of the pawl and ratchet is found where the pawl is designed with two stops, one at each end of a half moon, with a pivot in between, and an arm to actuate the pawl. This design limits motion of the ratchet to "one click at a time". The lever arm must be operated for each tooth. Motion of the lever causes the unengaged trip stop to bear upon a tooth, hold the ratchet, and at the same time cause the engaged positive stop to slide out of contact with its tooth. The lever can then be released, as pressure of the tooth on the trip stop will cause the positive stop to become engaged and prevent further motion of the ratchet.



Rotation of some integrator disks which represent TIME are good examples of the need for accuracy. If the input provided by an integrator is not accurate, the change in range will be equal to the inaccuracy multiplied by the change in range rate. The motor regulator keeps the time motor running at a constant speed, regardless of load variations.

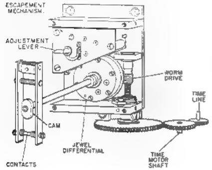
The motor regulator assembly monitors the operation of the time motor, which is characteristically geared to turn the "time line" too fast if power is supplied to it continuously. When the motor begins to increase rpm, contacts break the circuit, and close again when the motor slows down to normal operating speed, thus keeping the time motor speed practically constant.

OPERATION OF MOTOR REGULATOR

The time motor is geared to drive the time line and a worm drive. The worm drive transmits the rotation of the motor shaft to a spider in the differential, which compares the motor speed with the constant escapement speed. If the motor drives the differential spider faster than the escapement, this difference will cause a cam to spread a pair of switch points and break electrical contact. Return to normal speed allows the cam to turn and permit the contacts to close again. The cam continuously opens and closes the contacts as motor speed becomes slightly greater or less than escapement speed. This action takes place so fast that motor speed is always closely matched with escapement speed. The average speed of the time motor output shaft is constant.

PARTS OF MOTOR REGULATOR

There are three main components: (1) the escapement mechanism, (2) the jewel differential, and (3) the cam and contact assembly. The illustration depicts these items in relation to the time motor and time line.



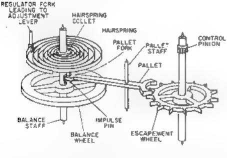
ESCAPEMENT MECHANISM

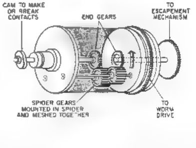
The escapement mechanism is in essence the escapement of a mechanical clock. In a clock, the escapement is an integral part of the mechanism, but in other cases, as in regulators, the escapement is made up as a separate unit and bolted into place. Its gear is meshed with the jewel differential in the regulator. Divested of housing, the principal remaining parts of an escapement mechanism would appear like this:

Continued swing frees the escape tooth, and at the same time the stop tooth comes into play to halt further movement of the escapement wheel. The pallet lever in the meanwhile has applied pressure to the impulse pin on the balance wheel and caused it to rotate and "wind up" the hair spring. Winding the hair spring slows up, stops the balance wheel, and then as the spring starts to unwind, puts pressure on the prong of the pallet fork. The hair spring unwinds, spins the balance wheel in the opposite direction, and moves the pallet lever to repeat the cycle. The result of oscillation of the pallet lever is to allow release of the escapement wheel one tooth at a time. Since there is a definite and even rhythm of the balance wheel, the control pinion is held to a definite, constant speed. By fitting a little fork over one of the last turns of the hair spring, to control its wind up, control is had of the balance wheel oscillations. By extending the arm of this control to some accessible position on the escapement mechanism, a means of speeding up or slowing down the action is provided. Thus, a number of escapements can be adjusted so they all operate at the same speed. By moving the adjustment lever to F (for faster) and to S (slower), the oscillations can be made to increase or decrease in tempo.

THE JEWEL DIFFERENTIAL

This spur gear differential has come to be known as a jewel differential because jewel bearings are used to reduce friction drag to a minimum. Its spider is comprised of a case enclosing end and spider gears, secured to a large driven gear. One of the end gears is mounted on a shaft extending out of the case and provided with a gear. The escapement regulates the speed of this gear. The other end gear, driven through spider gears, turns the cam of the cam and contact assembly. The escapement mechanism tends to turn at a constant speed. Motor speed varies. The difference between these speeds drives the output side of the differential turning the cam.





The spur gear, mounted on the escapement wheel shaft, acts as the input for the escapement and at the same time as the control pinion for the mechanism it is to control. Rotation of the escapement wheel applies pressure on the escape tooth of the pallet. This causes the pallet fork to swing on its staff.

When the motor speed is greater than the escapement speed, the cam turns, opens the contacts and, by removing power, permits the motor to slow down. When motor speed is less than escapement speed, the cam turns to permit the contact to close. With power applied, motor speeds up again.

CAM AND CONTACT ASSEMBLY

The cam and contact assembly consists of two arms pivoted together, each arm bearing a roller and a contact. A spring pulls the two arms together. When the cam located between the roller is turned so it pushes the rollers and switch arms apart, the contacts are separated, breaking the electrical circuits. With contacts closed, motor turns on. As speed is less than escapement, cam remains in a position where arms and contacts are pulled together by the spring. Motor will continue to speed up and, when speed becomes greater than escapement, cam is turned, spreads arms, and opens the contacts. The motor slows down and, when speed is less than escapement, cam moves to allow switch contacts to close and again apply power to motor.

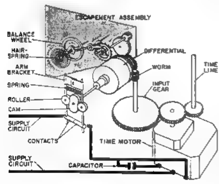
Cam is vertical. Contacts are closed when motor is turned on.

Motor speed is greater than escapement speed. Cam turns. Contacts open and motor slows down.

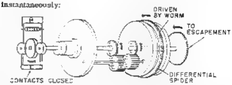
Motor speed is less than escapement speed. Cam returns toward vertical position. Contacts close and motor speeds up.

STEP-BY-STEP OPERATION OF MOTOR REGULATOR

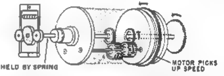
Here is the step-by-step operation of the motor regulator (escapement mechanism, jewel differential, and the cam and contact assembly) hooked up with the time motor. The essential elements and electrical hook-up of the time motor may be shown like this:



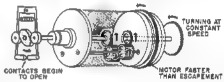
When the motor is turned on, the following occurs almost instantaneously:



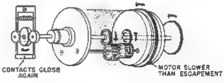
With contacts closed, current goes to time motor and causes worm to drive spider. The cam begins to turn. Almost immediately the cam strikes the rollers on the switch arms. The spring between the arms acts as a slight brake so contacts do not open at once.



Following the line of least resistance, the motion from the spider backs into escapement mechanism which picks up speed. Meanwhile time motor has been increasing its speed. The escapement mechanism is moving at the maximum speed which the coiling and uncoiling of the hairspring will allow.



When the rotation of spider can no longer back into escapement, it turns the other side of the differential on which the cam is secured, opening the contacts. The motor slows down.



As soon as the motor speed falls a little below escapement speed, the cam will no longer hold the contacts apart. The spring will bring the arms together, turning the cam toward its vertical position and allowing the contacts to close again. The cycle then starts over again, the cam continuously opening and closing contacts as the motor speed becomes slightly greater or less than the escapement speed. This happens so fast that the motor speed is always closely matched with the escapement speed. The average speed of the motor output shaft is constant.

PROBLEMS

1. In the case of a traveling nut stop additionally equipped with electrical stop switches, would the mechanical stops or the electrical switch stops be used for initial stops? Why?

2. What advantage has the Oldham coupling over the flange-type or clamp-type couplings?

3. After reinstalling a drive involving an Oldham coupling, what very important item should be checked before starting up the equipment?

4. When vibration and the fluctuating velocity common to the cross pin universal point would be objectionable, what other type of universal joint could be used in its place?

5. In high-speed equipment, why is the solenoid clutch a favored means of control?

6. Why is a solenoid lock used in some equipments?

7. What is the function of a friction relief device?

8. When would the use of a friction-holding device be indicated?

9. Of what would a simple intermittent drive consist?

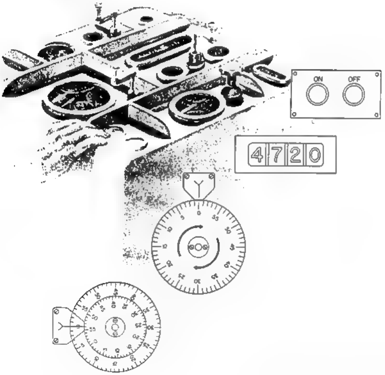
10. What kind of handcrank would be used to prevent feedback or motion from backing up the crank?

11. Where would you expect to find a vernier gear clamp?

12. Explain the purpose of a detent.

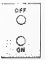
SECTION 7

DATA PRESENTATION



Ordnance equipment requires the transmission, reception, and direct reading of information. Indicators, counters, scales, and dials are used to display or correlate this data. They serve also for adjustment, alignment, and checking purposes. Each of these indicating means is designed for a specific application.

If you were asked to name one of the simplest of indicators, you might refer to the arrow on a sign post pointing the way to a town or place.



WALL SWITCH

Another familiar indicator is the light switch with two push buttons, one marked OFF and the other ON. Button positions show when current is off or on.

PUSH-PUSH TYPE SWITCH

TOGGLE SWITCH

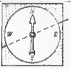
A later version of the push button switch is the PUSH-PUSH type which makes use of a single button. Repetitive pushes on the button turn the lights ON or OFF. Some switches have a toggle which indicates OFF or ON by its position (up or down; left or right), also used to indicate what circuit is being energized.

The multiple selector switch is used where several electric circuits are involved. Turning a knob and its indicator to the proper numeral or legend cuts in the desired circuit.

MULTIPLE SELECTOR SWITCH

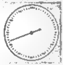
A rheostat or potentiometer also has a knob and indicator. By turning the knob, the desired electrical resistance can be secured, ranging from zero to the highest indicated capacity of the instrument.

POTENTIOMETER



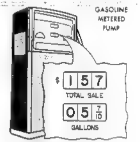
COMPASS

The pointer of a compass indicates magnetic north. Points relative to this position can be determined. The compass might be called a visual relative position indicator, for if we have a map, or know the area, we can travel over a selected course in the proper direction.


SWEEP SECOND HAND


CLOCK WITH SWEEP SECOND HAND

The sweep second hand, presenting elapsed time in seconds, is another familiar indicator. If we were interested in a time operation, we would use a timer provided with a minute hand so geared that for each sweep of the second hand representing 60 seconds, the minute hand would move an increment representing 1. The next step would be a clock with three hands to indicate hours, minutes, and seconds. Such a clock could be a special one with a standard 12-hour dial (as shown), or it could have a Navy type 24-hour dial.



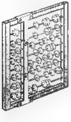
GASOLINE METERED PUMP

Gasoline pumps usually have dual indicators, one window showing total flow of fuel in gallons and tenths of a gallon, and another window showing cost in dollars and cents. They may be called simple computers.

COUNTERS

ABACUS

Counting and other forms of arithmetic have been performed for ages using the simple abacus. To keep track of the numbers involved, beads are moved on wires within a frame.



THE TAFFRAIL LOG

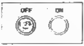
The taffrail log was used to obtain the speed and daily run of a ship. A rotor at the end of a line was trailed in the ship's wake, and a counting mechanism, mounted on a gimbal at the taffrail, counted the revolutions of the rotor.

REVOLUTION COUNTER

By coupling a mechanical counter to a rotating shaft, while timing with a stop watch, shaft rpm can be counted.

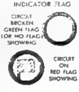
Additional and sometimes remote visual indicators, or tell-tales, can be used to indicate circuit conditions. A small electric lamp, mounted under a colored lens, lights to indicate the conditions. One lamp, under a green lens, may be used to show the circuit is OFF. Another lamp, under a red lens, may be used to show that the current is ON.

INDICATOR LIGHTS



By using a small electro-magnet or solenoid as the control, an effective indicator was developed. The energizing or de-energizing action of the coil is used to cause a pivoted flag to appear in a window. When current is ON, a red flag appears in the window labelled CURRENT ON. When current is OFF, a green flag appears in a window labelled CURRENT OFF, or CIRCUIT BROKEN.

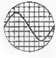
INDICATOR FLAG



OSCILLOSCOPE

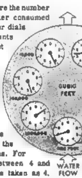
The cathode ray oscilloscope is one of the most perceptive electronic test instruments. The fluorescent screen gives visual presentations of current voltage, and circuit waveforms. The tube is also used as an indicating device for displaying data obtained by using radar, sonar, radio direction finders, loran and television.

SINE-WAVE VOLTAGE PRESENTATION

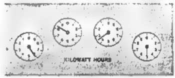


SAW-TOOTH WAVE FORM

Water meters measure the number of cubic feet of water consumed by means of indicator dials which show increments from one cubic foot to millions of cubic feet. Because of the train of gears used, the dials are read alternately, one dial from left to right, and the next from right to left. The readings are taken by using all of the lowest dial indications. For instance, a hand between 4 and 5 on a dial would be taken as 4.



ELECTRIC METER

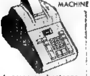


Gas meters are also calibrated in cubic feet, and indicate in the same way as water meters.

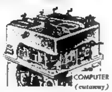
Electrical meters use a small amount of current to actuate indicating mechanisms, and to move pointers over dials. These meters indicate electric current consumption expressed in kilowatt-hours.

COMPUTERS

ADDING MACHINE



A common business computer, the adding machine, is used to total numerical inputs fed into it. The count is indicated on the edge of interconnected wheels viewed through windows in the case.

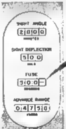


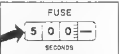
COMPUTER (cutaway)

A computer used in gunfire control receives inputs of numerical values, performs computations, and delivers an answer, or transmits it as output information. These quantities are counted in units such as yards of range, degrees of elevation, or knots of ship speed, each expressed as a number.

PREDICTION VALUES GROUP COUNTER

The Prediction Values Group on the top of Computer Mk 1 is an example of more involved counter presentations. Here, the Sight Angle counter shows a computed value in minutes. The Fuse Counter displays the computed value of the fuse setting order in seconds. The first two figures are in white, and give readings in full seconds.





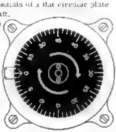
The third figure is in red, and the graduations are in tenths of a second. By observing the relation of the graduations to the index, hundreths of a second can be approximated.

A dial is a convenient means of displaying data by means of its rotation. A small angular displacement may be read against a fixed index, or against a graduated outer ring. Some dial arrangements display two values or quantities for comparison. Dials can be positioned by hand cranks, or automatically. There are two general types: disk and ring.

disk dial

The disk dial consists of a flat circular plate secured to a shaft.

The disk may be calibrated about its entire circumference, registering against a fixed index. ■ a reading in seconds was desired, we could take a dial with its circumference marked off into 60 equal spaces, each representing a second.

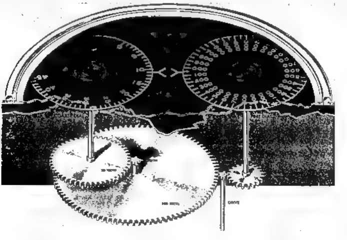


An equivalent arrangement is a disk bearing only an index, rotating so that the index points ■ graduated values on a fixed ring or on a separately mounted face plate.

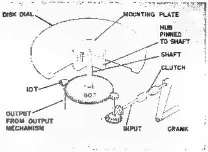
LINEAR DIALS

Linear information may be expressed by the use ■ one or two dials. Double speed disk dials, for example, offer a means of expressing linear data by the use of one coarse dial and one fine dial. The pair of height dials in a typical computer indicate the vertical height of a target. The coarse dial, graduated every 1000 feet, is numbered every 5000 feet up to 50,000 feet. End zeros are omitted to permit the use of larger, easier read figures. The fine dial is graduated every 50 feet, and marked every 100 feet. These dials are gear-driven from the same drive shaft.

■ reading dials of this kind, the coarse dial ■ read against the index at its indicated or next lowest value point. The fine dial reading is taken at its indicated or highest estimated point between value points. The dials shown register 11 (11,000) on the course dial, and ■ on the fine dial, making the total 11,060 feet.



DIALS INPUTS AND OUTPUTS

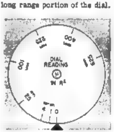


Disk dials are suitable for indicating linear or non-linear values, expressed as inputs or outputs. Our previous example of a dial may be imagined as secured to a shaft to which a gear is attached. If this gear has 60 teeth, the dial would be moved one second for each tooth movement. Total movement would be indicated by the output from some other mechanism.

If we add a crank and a clutch, we could feed in information, thus reversing the process. We could crank in the desired time input indicated on the dial, and delivered as an output to the other mechanism.

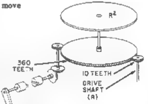
NON-LINEAR DIALS

Within limits, dials are suitable for indicating non-linear functions. For example, parallax range is transmitted to the guns by a single speed transmitter. The transmitter dial is graduated [illegible] yards, marked from 1,555 to 30,000 yards, and infinity. Spaces between graduations vary inversely with the advance range; that is, as range increases, the spaces between graduations decrease. As a result, there is crowding at the long range portion of the dial.



Let us consider the opposite case, and construct a dial with graduations progressively further apart as values increase. To illustrate this, we could have a dial indicate the square (R^2) of the revolutions (R) of a shaft. Assume only a few readings are required, as for 0, 1, 3, 5, 10, 15, 20 and 25 shaft revolutions.

A quick appraisal indicates that a simple reduction gear would solve the problem of drive between shaft and dial. To simplify the problem of dial layout, let us secure to the dial a gear with 360 teeth, and use as the drive from the shaft a pinion with [illegible] teeth. Each shaft revolution (R) would move the dial gear 10 teeth, and advance the dial reading 10 degrees.



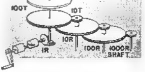
We can make up a table covering these conditions, and use it to calibrate the dial, thus:

R of Shaft	R^2 Reading on Dial	Position on Dial (degrees)
0	0	0
1	1	10
2	4	20
5	25	50
10	100	100
15	225	150
20	400	200
25	625	250

Note the numerically progressive difference between 0 and 5, 5 and 10, etc.

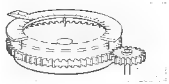
We could add a crank to our mechanism to set in the desired R value to be transmitted as shaft revolutions.

If greater ratios are involved, it would be necessary to use more extensive reduction means, such as a gear train using as many reduction combinations as required.

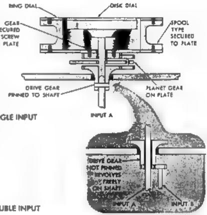


ring dials

A ring dial is shaped somewhat like a washer. It may be mounted on posts to raise it above its mounting plate or gear, or it may be spool-shaped for direct mounting on its plate. Increments may be inscribed at inner or outer diameters, depending upon application. The outer edge, presenting greater linearity, lends itself to fine readings. The ring can be driven by pinion or planet gearing.



While ring dials may be used alone, they are often combined with disk dials. The ring dial allows a disk dial to be placed within the hole at its center. With both inscribed dial faces on the same plane, they are easily matched, compared, or arranged to render a differential reading. The disk dial can be mounted directly on a drive shaft or differential spider, and also drive planetary gearing [illegible] control motion [illegible] the ring dial. A typical design is one in which the ring dial revolves one turn to 18 turns of the disk dial, providing mechanical interdependence of dials, and assuring accurate correlation. Another means of operation, where two inputs are involved, [illegible] to use the shaft as input A to the disk dial, and [illegible] provide the ring dial drive gear with a spur gear, so [illegible] may be driven by input B. [illegible] this case, the ring dial drive gear is not pinned to the shaft, and [illegible] free to revolve independently of it. Further, the ring dial may be driven by means of a simple gearing, or by a more complex gear train, depending upon the requirements of the particular application.



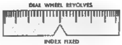
SINGLE INPUT

DOUBLE INPUT

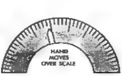
MISCELLANEOUS DISPLAYS

An indicator used for meter work consists of an index moved over a fixed scale [illegible] a straight line.

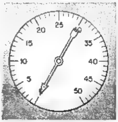
Another type uses a revolving drum dial, which is read against a fixed index.



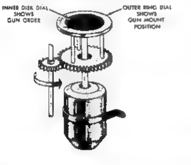
A common indicator used on electrical instruments is the hand or pointer index moved over a semi-circular scale.



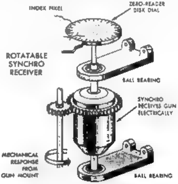
The pressure gage, its scale calibrated in pounds of pressure per square inch, is another fixed scale. The compound gage provides means of reading pressure above zero (the pressure existing [illegible] sea level), and for values below zero, in inches of vacuum.



An arrangement using ring and disk dials is the follow-the-pointer mechanism used to indicate movement of a gun mount in elevation (or train) in response to the gun order. A synchro receiver, to which is fed the signal representing the gun order, drives a disk dial. The ring dial is geared to the gun mount, and it follows the transmitted signal (follow-the-pointer). When a gun order is changed, the synchro receiver rotor turns the disk dial, and the mount power drive (or gun pointer, or gun trainer) responds by moving the gun according to the indicated order. This movement also drives the response gearing, turning the ring dial to follow the inner synchro driven disk dial. When the two index marks match, the gun mount is in gun order position. Note that the synchro body (and stator) is clamped in a fixed position.



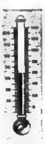
The zero-reader mechanism is used to operate a disk dial which displays response of a gun mount or other application to a synchro signal. The zero-reader mechanism uses a synchro receiver which permits the synchro stator to be mechanically rotated. The example illustrates a receiver which receives a synchro signal representing a gun order (elevation or train). This causes the synchro rotor to turn, turning the zero-reader disk dial off the fixed index mark. As the gun mount is moved (automatically by power drive, or manually by gun pointer or trainer), the entire synchro (including the dial) is rotated through gearing toward the fixed index mark. Synchro rotor and stator are electrically locked together by their magnetic fields. This causes the stator, rotor and dial to rotate as a unit toward the fixed index mark. The zero-reader dial shows the difference between gun order and response. When the two are equal, the difference is zero. When indexes are matched, with the dial indicating zero, gun mount position corresponds to gun order position. The process of matching indexes is called matching zero readers.

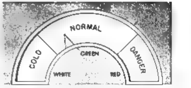


THERMOMETERS

THE STEM THERMOMETER

The stem thermometer, consisting of a calibrated glass tube with a fine bore, is read by observing the height of the indicating fluid, such as mercury or tinted alcohol. The dial thermometer uses a hand sweeping across a calibrated dial to indicate temperature. A thermal indicator, used in automotive devices, employs a hand which sweeps over colored or labelled sections of a dial to indicate specific conditions. When its hands points to "Cold" section, which may have a white background, it indicates that the device is not up to operating condition. When the hand points to the middle section, with a green background, it indicates that the device is in normal operating condition. When the hand points to the red section, it indicates an overheated condition.





THERMAL OPERATION INDICATOR

summary

Data presentation is the visual indication of a position, quantity, or condition. The information presented may be simple (shaft rpm), or complex (circuit voltage analysis on an oscilloscope). The data is displayed in terms representative of the appropriate units of measurement. The information is presented on inscribed counters, dials, or scales.

PROBLEMS

1. Refer to the illustration showing the dial of a water meter. What is the reading?

2. In a plant or home equipped with a water meter, how would you determine the quantity of water consumed during the past month?

3. How many kilowatt-hours are indicated on the illustration showing the dial arrangement of an electric meter?

4. What are the two common dial forms?

5. Name two types of indexes.

6. What is the process involved in "following a pointer"?

7. On what type of dial mechanism would you apply the term "matching pointers"?

8. What does a "zero-reader" dial show?

9. Explain what takes place when a gun order is transmitted to a zero-reader synchro receiver.

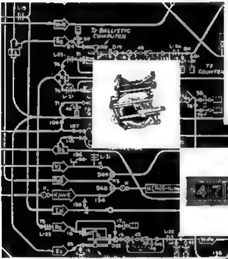
10. Refer to the illustration of height dials showing a total reading of 11,060 feet. Suppose a pinion with 5 teeth is used on the drive shaft, and a gear with 20 teeth is used on the fine dial shaft. As the fine dial has a total of 10 numbered points (in hundreds), and 10 midway points (representing 50-foot increments), there is a total of 20 points on the dial. A movement of one tooth of the drive gear would cause the dial to be moved one 50-foot increment. If the drive pinion makes four revolutions, the fine dial would make one revolution representing 1,000 feet. Our problem concerns the coarse dial shown in the illustration. Work out the following:

    (a) How many teeth are required for the gear on the coarse dial shaft?
    (b) How many teeth are required on the pinion of the coarse dial shaft?
    (c) How many teeth are required on the reduction gear driven by the drive shaft pinion?

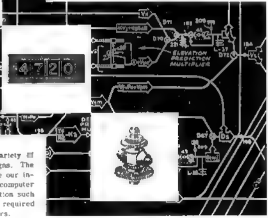
11. Refer to the illustration covering R^2 dial readings. Assume we wish to have this dial take care of all the readings shown, and in addition, to show R^2 readings for 30R, 35R, and 40R. Explain how this can be accomplished, and use a sketch to illustrate the dial layout, giving the R^2 readings and positions on the dial.

SECTION 8

application of basic mechanisms in
COMPUTING SYSTEMS



The student is familiar with the basic mechanisms. Each one of these is a small computer in itself, but its function is limited. It can perform only one type of operation, such as: addition-subtraction, multiplication-division, etc. Many problems involve more complex operations and combinations of the basic operations. To handle these problems, many basic mechanisms must be used together in a computer. By applying his understanding of each basic mechanism discussed in chapter 2, the student can analyze and understand many of the most complicated computing systems.

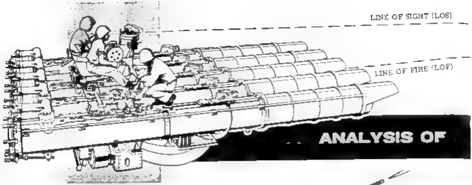


Because computers are used for a large variety of purposes, they may have many varied designs. The particular type of computer which will engage our interest is that used in fire control. The job of a computer in fire control is to convert available information such as speeds, locations, and ballistic data into required information such as fuze settings, and gun orders.

scope of section

In this section, a computing system is designed to solve a basic fire control problem. First, the problem is analyzed in a geometric way to determine what preliminary information is required. Then, the means of securing this information is devised. The preliminary information is then mechanized in a computer in order to calculate the required information.

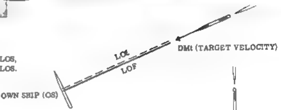
The design of a computer system will not be approached from a "nut and bolt" point of view. The computer will be looked upon as being composed of several basic mechanisms, connected in a certain way, to perform a particular task.



ANALYSIS OF

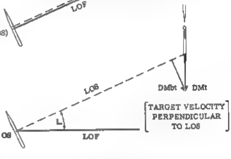
target velocity on LOS

When the target velocity is solely on the LOS, the LOF is made to coincide with the LOS.



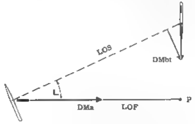
target velocity across LOS

When the target has a component of velocity perpendicular to, as well as along the LOS, the torpedo must be fired in front of the target to hit it. The LOF must lead the LOS by angle L.



Angle L is the desired output of the fire control system. The computer must determine this value from the information supplied to it.

Angle L depends on both the target speed (DMt) and the torpedo speed (DMa). It must be adjusted to cause the torpedo to reach a future point P at the same time as the target.



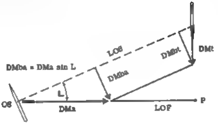
For a mathematical solution to the problem, an equation with angle L as the only unknown will be established.

A system is required to provide the firing information necessary to hit a moving target with a torpedo fired from a surface vessel.

FIRE CONTROL PROBLEM

determination of lead angle

In order to reach point P at the same time as the target, the torpedo is fired at an angle so that it has the same component of velocity perpendicular to LOS (DMba) as the target (DMbt).



When

$$DMbt = DMba$$

Then

$$DMbt = DMba = DMa \sin L$$

and

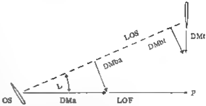
$$L = \sin^{-1} \frac{DMbt}{DMa}$$

When DMbt and DMa are known, L is determined by solving the above equation. The determination of the required information will be discussed on the following pages.

MECHANIZATION OF

The original statement of the fire control problem — directing a torpedo at a distant target — is vague. The physical requirements of the fire control system are not apparent from the problem statement itself. After analysis, however, the requirements are more specific. We have the equation:

$$DMbt = DMba = DMa \sin L$$



TRACKING

analysis of rate measurement problem

In the lesson on rate measurement a method was outlined for approaching any rate measurement problem. We will follow that method.

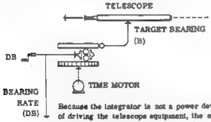
1. Component to be Measured — Quantity needed is target speed perpendicular to LOS (tangential speed DMbt).

2. Direct or Indirect Measurement — Indirect method is used because direct method cannot be applied unless physical contact ■ established with the target.

3. Type of Duplication — Linear tracking (following the target) is impractical. The type of duplication which will most easily give DMbt is rotational tracking. Radar or telescope sighting may be used to duplicate the motion of the target. For simplicity, let us assume that the target is tracked with a telescope.

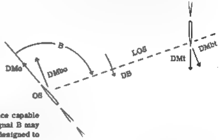
solution of rate measurement problem

In the calculation of DMbt, the bearing rate must first ■ measured. The speed control, arranged for measuring speed and bearing, is as follows:



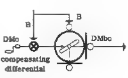
Because the integrator is not a power device capable of driving the telescope equipment, the signal B may be applied to a servo system which is designed to drive the telescope equipment.

The calibrated speed control determines bearing rate, DB, which is the angular velocity of the telescope.



PRELIMINARY INFORMATION DMbo AND B REQUIRED IN DETERMINATION OF DMbt

DMbo is the tangential component of DMo, own ship speed. DMo is measured by a pitometer log, a direct speed measuring device. By putting DMo and B (the target bearing determined by the speed control) into a component solver, component DMbo may be calculated.



FIRE CONTROL PROBLEM

The problem can now be divided in two parts:

1. Using known methods of rate measurement, find DMbt. As the method usually used in step 1 involves following a target with radar or telescope, step 1 is called tracking.

2. Using DMbt and other available information, find L. Since angle L indicates predicted or future position of LOS at the time the torpedo hits the target, step 2 is called prediction.

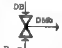
DETERMINATION OF DMbt

The position of the telescope gives target bearing. The rotational speed of the telescope gives bearing rate.

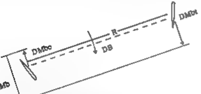
4. **Measurement of Duplicate.**
   The three methods of measurement are:
   a. Clocking
   b. Speed Sensitive Device
   c. Calibrated Speed Control

The method used in most fire control applications [redacted] c, the Calibrated Speed Control. This method [redacted] used because it [redacted] fast, gives instantaneous values of speed and allows the operator to change the duplicate speed by changing the setting on a calibrated control rather than cranking by hand.

Multiplying the bearing rate DB, by the range of the target, R, determines DMb, the relative tangential velocity between own ship and the target.

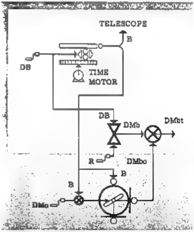


PRELIMINARY INFORMATION DMbo AND R MUST STILL BE DETERMINED



Subtracting own ship tangential velocity DMbo from DMb, we get DMbt, the tangential target velocity.

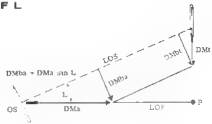
Target range, required in the determination of DMbt, can be found by an optical rangefinder, radar or other means. We will assume that range can be continuously measured and cranked into the multiplier.

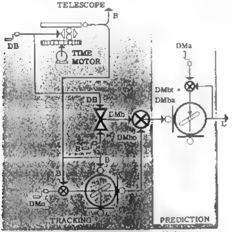


The tracking section is now complete. The output of the tracking section is DMbt. The inputs to the tracking section are DB, R and DMo.

PREDICTION...... DETERMINATION OF L

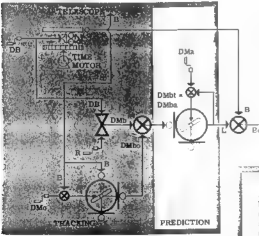
Prediction in torpedo fire control consists of calculating angle L, the angle which the LOF makes with the LOS. This calculation can be made by a vector solver from information supplied by the tracking section.

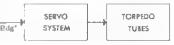




The speed of the torpedo, DMa, is manually adjusted and is, therefore, a known quantity. DMba is known because it is equal to DMbt, the value calculated by the tracking section. By putting DMa and DMbt into a vector solver, the sight angle, L, is calculated.

Angle L between the LOS and LOF, when added to the target bearing B, gives the tube train Bdg' with respect to the ship centerline. This value can be sent by means of synchros and servos to the torpedo tubes.

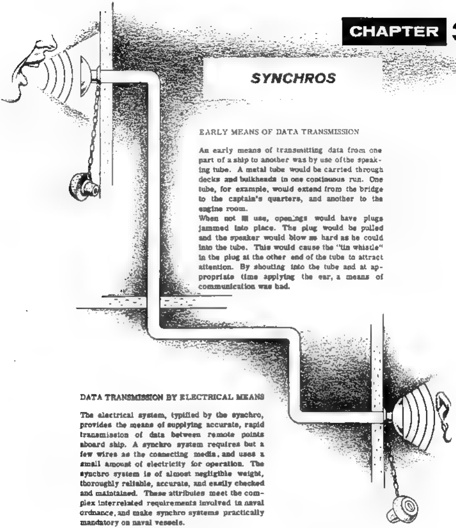




The inputs to the system as a whole are R, DMo and DMa. DB is cranked in by the telescope observer. The observer can be considered as part of the system. (In that case the error observed when the target was not directly in the telescope crosshairs would be an input.) The output of the system is Bdg' (torpedo tube train).

SUMMARY

Although such a system as developed in this section could be used to calculate lead angles, most actual systems are more complicated. The extra complexity is mainly due to automatic features. A typical fire control system would not require range and DB to be constantly cranked in. As a target moves with constant speed and course, the range and bearing rate may change. Computing systems are designed to automatically compensate for these changes.



CHAPTER 3

SYNCHROS

EARLY MEANS OF DATA TRANSMISSION

An early means of transmitting data from one part of a ship to another was by use of the speaking tube. A metal tube would be carried through decks and bulkheads in one continuous run. One tube, for example, would extend from the bridge to the captain's quarters, and another to the engine room.

When not in use, openings would have plugs jammed into place. The plug would be pulled and the speaker would blow as hard as he could into the tube. This would cause the "tin whistle" in the plug at the other end of the tube to attract attention. By shouting into the tube and at appropriate time applying the ear, a means of communication was had.

DATA TRANSMISSION BY ELECTRICAL MEANS

The electrical system, typified by the synchro, provides the means of supplying accurate, rapid transmission of data between remote points aboard ship. A synchro system requires but a few wires as the connecting media, and uses a small amount of electricity for operation. The synchro system is of almost negligible weight, thoroughly reliable, accurate, and easily checked and maintained. These attributes meet the complex interrelated requirements involved in naval ordnance, and make synchro systems practically mandatory on naval vessels.

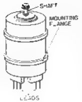
scope of section

This section will be devoted to synchro devices in which the different types, separated into related groups, will be outlined. These groups will comprise:

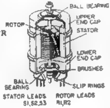
- Synchros . . . Transmitters and Receivers
- Synchro Differentials
- Synchro Control Transformer
- Synchro Capacitors
- Transmission Speeds
- Zeroing Synchros

HOW THEY ARE BUILT

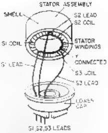
TYPES OF SYNCHROS
While a synchro has the outward appearance of the familiar fractional horsepower motor, its wiring and coil arrangements are different. There are several types and sizes of synchros for a variety of purposes.



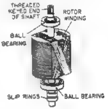
SYNCHRO TRANSMITTER
A synchro transmitter is composed of two major parts: a stator, and a rotor, enclosed within a dust-proof housing.



STATOR
Inside the stator shell are three windings or coils, spaced 120° apart, and wound into the slots of the laminated iron field. One wire is taken from each coil and joined to form a "Y" connection, so-called because the leads form the three spokes of a Y. A lead is soldered to the other end of each winding, and brought out through a guide block on the lower cap. To identify their respective coils, these leads are labelled S1, S2, and S3.



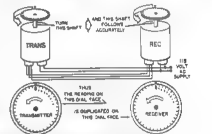
ROTOR
The rotor consists of a precisely shaped soft iron core mounted on a shaft, and provided with a single winding whose axis is coaxial to the shaft. Coil ends are secured to insulated slip rings mounted on the shaft. Two brushes bear upon the slip rings when the rotor is assembled in the stator. A rotor looks like this:



WHAT SYNCHRO TRANSMITTERS AND RECEIVERS DO

SYNCHRO TRANSMITTERS AND RECEIVERS
The important feature of synchros is that they are inherently "self-positioning" or synchronizing; this explains the name synchro. This synchronization can be checked by electrically connecting a synchro transmitter with a synchro receiver. Identical dials affixed to both shafts will read the same, thus:

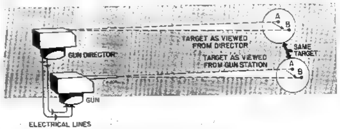
SELF-SYNCHRONIZING CHARACTERISTIC
They are used in many points in fire control systems to transmit information. The transmitter sends out the signal; the receiver turns its dial or pilot control correspondingly to position other mechanisms. The principle of the synchro arrangement is that when the transmitter shaft is turned, the receiver shaft will turn, and position a remote mechanism exactly the same amount.



WHAT SYNCHROS ARE USED FOR

The synchro team of transmitter and receiver can be used in a number of ways. We know it can be used to directly position a synchro receiver dial so the data transmitted from one station can be read directly by reference to a synchro receiver dial distant from it.

For example, a synchro system can be used to transmit a training order from a gun director to a gun. The synchro transmitter, mounted in the director and geared to it, transmits the movement and position of the director. The dial of the synchro receiver at the gun constantly indicates the director's position. Thus, if the director aimed at A, is then trained to B, the synchro receiver at the gun will receive and indicate this so the gun can be trained until its position agrees with the new data.



. . TRANSMITTERS AND RECEIVERS

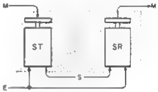
We can use symbols and letters to identify the synchros, and thereby quickly make up or interpret diagrams. By means of labelled lines and directional arrows the flow of inputs, outputs, and electrical supply (115-volt 60-cycle AC) can be indicated. Let us label inputs and outputs as:

M = mechanical
E = electrical supply (115-volt 60-cycle AC)
S = synchro signal (AC voltage)

We can represent the synchro as an oblong box, with a shaft and dial on top. By using the first letter of each word comprising the name of the synchro, we have a quick means of identification. Thus, ST would represent a synchro transmitter, and SR a synchro receiver. By placing the proper letters in the synchro box, we can readily identify it. Later we will use other synchro names in the same way and identify the synchro boxes by means of their first letters. To illustrate the use of the diagram and symbols, we would draw the simple synchro transmitter and synchro receiver system like this:

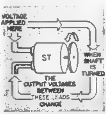
Note how mechanical input (setting) feeds into the synchro transmitter. Energized by the electrical supply, the transmitter causes a synchro signal to be sent to the synchro receiver which is also energized, resulting in identical mechanical output at this end of the system. We can set up a table to show this as:

SYNCHRO UNIT	INPUT	OUTPUT
Transmitter (or Generator)	Electrical and Mechanical	Synchro
Receiver (or Motor)	Electrical and Synchro	Mechanical

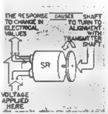


As long as power is supplied, both dials will read the same, the synchro receiver following changes made to the synchro transmitter setting. With the power disconnected synchros become independent of each other. If we set the synchro transmitter to any selected reading, and now apply power, the synchro receiver will then respond immediately to show this particular setting of the synchro transmitter.

This responsive action takes place because the pair of synchros with

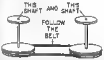


wires joining them to carry the signals, and other wires to a power



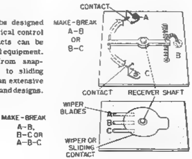
source to energize the circuit, comprises an electrical system.

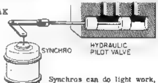
The synchro system acts similarly to a pair of identical pulleys connected with a belt, like this:



SIMPLE TWO CONTACT MAKE-BREAK

A synchro system can be designed to make or break electrical control circuits, whereby contacts can be used to control electrical equipment. Such contacts range from snap-action make-and-break to sliding or wiper blade types in an extensive number of combinations and designs.



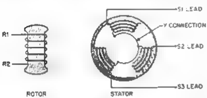


Synchros can do light work, such as operate or position pilot valves to control hydraulic equipment.

Synchros provide the most versatile form of remote control, and are used to operate or pilot operation of many kinds of equipment.

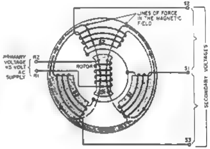
HOW SYNCHROS WORK

Electrical theory will be discussed here only to provide the elementary concept, omitting complex variances which will be taken up in the section devoted to AC electricity. The rotor and stator windings of a synchro transmitter, and of a synchro receiver, may be diagrammed this way:

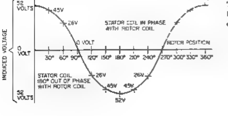


Note that each stator coil, depicted as an entity, actually represents all the wire which was wound in a number of slots. Synchro operation is based upon the transformer principle, involving a primary and secondary, as represented by the synchro rotor and stator. Rotor and stator are diagrammed to show the relationship, so it can be seen that when an alternating current is passed through the rotor winding, it sets up a changing primary magnetic field. Lines of force in this field cut through the stator coils, inducing a secondary voltage in each coil, depending upon the rotor coil position in relation to each stator coil.

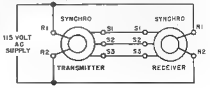
On an experimental synchro, a voltmeter could be connected across each coil, and individual voltages read, but on a standard synchro only the S1, S2, and S3 leads are available. Thus it is necessary to read the effective voltage by using a voltmeter across any two of the S leads (because of the Y connection), which involves reading the voltage of two stator coils. Effective voltage may consist of a plus and a minus voltage. For example, a +52 voltage induced in one coil combined with a −26 voltage in another would give an effective voltage reading comprised of the sum of the two voltages; that is, 78 volts. When 115 volts AC is supplied to a rotor coil, with the rotor in the position shown, lines of force in the magnetic field set up by the rotor will flow in the directions indicated by the arrows. Both sides of the field cut the S2 winding, while only one side of the field cuts the S3 winding and the S1 winding. A force of 26 volts is induced in the S1 winding because it is cut by only one side of the magnetic field, whereas the S2 winding (cut



A transmitter or receiver stator coil will attain a maximum of 52 volts when the rotor coil is in line with it (shaft in 0 degree position), and a decreasing voltage as the rotor turns away, until at 90° it reaches 0 volt. Current used to energize the rotor is single phase, 115 volt, 60 cycle AC. Polarity will change 120 times a second, 60 times negative and 60 times positive. A rotor, therefore, depending upon its coil polarity, may be in phase or 180° out of phase with the stator coil. A stator coil is in phase when the coil windings are in reverse of each other. A graph plotted to show the voltage induced in a stator coil by a rotor making a complete revolution, would appear as illustrated at the left.



The simplest synchro system is one comprising synchro transmitter and a synchro receiver, connected to each other electrically, and to a power source, like this:

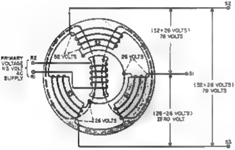


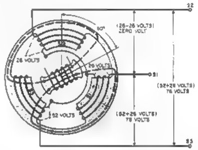
by both sides of the magnetic field) has 52 volts induced in it. As the stator coils are Y-connected, the 52 volts from S2 add to the 26 volts from the S1 winding, so when measured across the S1 and S2 leads, the total effective reading is 78 volts. In addition to indicating the paths of the rotor field, the arrows on the diagram indicate the phase relationship of the three Y-connected stator coils. Where the arrows passing through a stator coil point away from the rotor, the coil voltage is in phase with the R1-R2 voltage. When arrows through a coil point toward the rotor, that coil voltage is out of phase with the R1-R2 voltage. When combining the voltage of two coils that are both in phase, or both out of phase, the connections are such that the effective voltage is the difference between the two voltages. When combining the voltages of a coil in phase and a coil out of phase, the effective voltage is the sum of two voltages. If means were available to read the voltage of each stator coil, these readings would be as shown in the illustration below.

When voltage across S1-S3 is zero, and voltage across S2-S3 is 78 and [illegible] phase with the R1-R2 voltage, the rotor position is known as ELECTRICAL ZERO. This position is used in installation, testing, and setting a synchro.

If the rotor of the synchro transmitter is now turned through 60°, as shown below, the S3 winding will now have 52 volts induced in its winding, since both sides of the magnetic field cut this winding. The S1 and S2 windings have [illegible] volts induced in each. This shows that change [illegible] rotor position changes the voltages of the stator coils. No matter what position to which the synchro shaft is turned, voltages are induced in the stator coils. As a result, voltages appear between leads for any position it may assume.

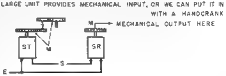
When the synchro receiver rotor is energized, voltages are induced in its stator coils in the same way [illegible] the synchro transmitter rotor since, electrically, the two synchros are identical in construction.





Electrically, the two synchro units are identical. The rotor shaft of the synchro transmitter is geared [illegible] (and its motion controlled by) some large unit. When the synchro transmitter rotor is turned by movement of the large unit the synchro receiver shaft and rotor will follow and accurately assume the new position if power is on. If power is off, and the synchro transmitter shaft is moved to a new position, the synchro receiver is not activated. When power is restored, the synchro receiver shaft will turn to assume the position of the synchro transmitter shaft, turning because of the electrical unbalance. The synchro receiver shaft will turn until the voltages induced in its windings are the same as those induced in the synchro transmitter windings, and then, in a state of balance, there will be practically no farther current flow. (As in the case of any transformer, primary windings draw some current even with no load on the secondary, and this slight current draw supplies losses and rotor magnetism.

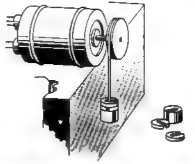
Change of synchro transmitter rotor shaft position causes an electrical unbalance, and a current flow, the currents being strongest when voltage unbalance is greatest. These currents in the synchro receiver stator coils provide an attractive force (torque) to turn the synchro receiver rotor toward the same position as the synchro transmitter rotor. Using the symbols used previously, we can show this as:



HOW TORQUE AFFECTS SYNCHROS

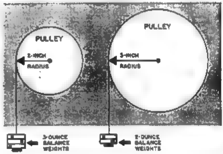
MEASUREMENT OF TORQUE

Torque, in a motor, is simply a measure of how much load it can turn or "lift". On small motors and synchro receivers, torque is measured in inch-ounces. A simple way to determine torque is to wrap a cord around a pulley secured to the shaft, and then add washers or small weights until the total weight is such that the motor is not capable of lifting the load, like this:



MEASURE OF PERFORMANCE

The radius of the pulley in inches multiplied by the balance weight in ounces gives the torque of the motor in inch-ounces. A 4-inch-diameter pulley loaded with a 3-ounce balance weight, would have the same inch-ounce rating as a 6-inch pulley loaded with a 2-ounce weight. To provide a measure of performance, synchros are rated at maximum permissible load values.



UNIT TORQUE GRADIENT

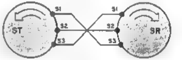
Specifications in catalogs and handbooks covering synchros list a rating called UNIT TORQUE GRADIENT. This rating refers to the inch-ounce per one degree difference in the synchro shaft position, when the synchro transmitter and the synchro receiver in a system are of the same size and construction.

Currents in the synchro transmitter stator coils cause a pull on the rotor, and the rotor tries to turn back toward the receiver's position. As the synchro transmitter shaft is geared to some large piece of equipment which the transmitter is not capable of moving, its rotor may be considered as locked in whatever position is dictated by the mechanical input. If measurements were made, the "pull" exerted by the synchro receiver on the synchro transmitter would be shown as a small but definite load on the large drive unit.

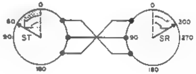
FACTORS AFFECTING SYNCHRO SYSTEM ACCURACY

The accuracy of a synchro system is probably its most important characteristic. Accuracy is determined by how nearly the shaft of the synchro receiver matches the position of the synchro transmitter shaft. A synchro transmitter and synchro receiver (or receivers) are generally connected for standard operation by having all similarly marked terminals joined, as S1 to S1, S2 to S2, etc. A synchro receiver can be made to operate so its shaft will turn in the direction opposite from that of the synchro transmitter, by connecting receiver terminal S1 to S3 of the transmitter, and receiver S3 to transmitter S1. Connected in this way, and with both transmitter and receiver initially set at 0, if the transmitter is turned counterclockwise 60°, the receiver shaft will turn clockwise to 300°, because maximum current flow is supplied to coil 3. The position of the receiver shaft can be determined by subtracting the transmitter position from 360°, as shown in the illustrations at the right.

STANDARD HOOK-UP
SYNCHRO RECEIVER SHAFT FOLLOWS TRANSMITTER SHAFT MOVEMENT



REVERSE HOOK-UP
SYNCHRO RECEIVER SHAFT TURNING IN REVERSE DIRECTION TO TRANSMITTER SHAFT



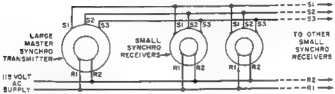
OPERATION OF DIALS WITH REVERSE HOOK-UP

OPERATION OF DIALS WITH REVERSE HOOK-UP

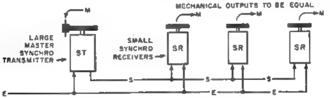
The S1-S3 leads are the only leads ever interchanged in a standard synchro system. Interchanging other pairs of S leads would introduce 120° changes in readings. Some friction in the synchro receiver is always present, regardless of how carefully it is designed and constructed. To overcome the drag of this friction, some torque must be present in the receiver. Since no torque is produced when the receiver is in the same position as the transmitter, it must lag slightly, and thus accuracy can never be perfect. To reduce friction to a minimum the ball bearings used on receivers are selected with extreme care, and lubricated with high grade light oil. Friction on the transmitter shaft does not affect the system's accuracy; it merely increases the power load on the large unit to which it is geared. Grease lubricated bearings are often used on transmitters. In the manufacture of synchros, it is common practice to select for receivers only those units having finer tolerances.

ONE TRANSMITTER CAN DRIVE MANY RECEIVERS

One large synchro transmitter may be used to drive a number of small synchro receivers connected in parallel, if the impedance of the transmitter stator windings is low enough to supply the current necessary to activate all the receivers without excessive voltage drop.



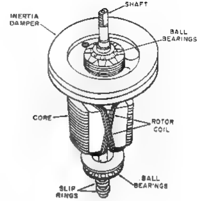
If one synchro receiver has to supply more torque than the others, its shaft will lag further behind the transmitter's, producing less opposing voltage in its stator coils, and therefore it draws more current than other receivers. This increased current will lower the synchro transmitter's output voltage, causing the other receivers to lag more than before. For accuracy, it is essential that the synchro transmitter have low impedance (a high Unit Torque Gradient), and that the load on each synchro receiver be as low as possible. Equal loads are important. In the multiple system, any unnecessary load on any one synchro receiver affects the accuracy of the entire system. Using our box diagram and symbols, we could show the action like this:



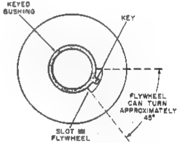
We can appreciate the advantage of a synchro system when we consider that the moment a signal is fed into the synchro transmitter, this data is immediately and simultaneously transmitted to all receiver stations, regardless of how remote or isolated each may be from the others on shipboard. Another advantage, from the military standpoint, is that the knocking out of a receiver station will not interfere with the operation of the remaining units of the system.

THE INERTIA DAMPER

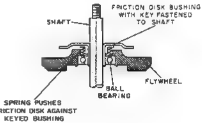
The synchro is similar to the small AC motor and, like such a motor, the synchro receiver (under certain conditions) had a tendency to spin continuously or "take off" at high speed. This is likely to happen when power is first applied to the system, and the shaft is suddenly turned. To prevent spinning, a device called an inertia damper is mounted on the output end of the receiver shaft, under the upper cap, like this:



The inertia damper consists of a relatively heavy flywheel with slot, mounted on a ball bearing. The flywheel turns freely on the shaft for about 45°; then, an edge of the slot strikes the key of a bushing. This bushing, riding on the shaft, is under pressure exerted by a spring and friction disk, so that it turns on the shaft with considerable friction. A typical damper would look like this:



Gradual changes in shaft position allow the inertia damper to follow without much effect. However, if the shaft is turned suddenly, the flywheel tends to stand still, and the friction disk then acts as a brake. The friction slows down the motion of the shaft, normally preventing it from going fast enough to start oscillating or spinning. If spinning occurs, it indicates something is wrong with the damper, or that a transmitter has been used in place of a receiver. In an emergency, a synchro receiver can be used as a synchro transmitter if a replacement transmitter is not available. But a synchro transmitter can not be used as a synchro receiver. Having no inertia damper, the synchro transmitter would oscillate or spin. Synchro transmitters, turned by gearing from a large unit, stop as soon as mechanical input ceases, and require no dampers.



The usefulness of a synchro system is greatly increased by the addition of another member of the synchro family, the synchro differential.

SYNCHRO

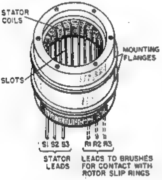
HOW THEY ARE BUILT

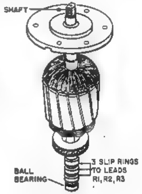
CONSTRUCTION OF STATOR

The stator of a synchro differential is similar to that used in the ordinary synchro, consisting of three sets of coils wound in slots equally spaced around the inside of the field structure. Coils are Y-connected, with leads brought out and labelled S1, S2, and S3 to identify the coils they serve.

CONSTRUCTION OF ROTOR

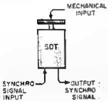
A synchro differential rotor is entirely different from that of the synchro transmitter or synchro receiver. It is cylindrical in form and similar to the stator in having three sets of Y-connected coils wound in slots. Three insulated slip rings are secured to one end of the shaft. Brushes in the stator assembly make connection with the slip rings, leads being out and labelled R1, R2, and R3 for identification.

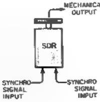




HOW THE SYNCHRO DIFFERENTIAL WORKS

The synchro differential is designed on the principle of a transformer wound for a one-to-one voltage ratio, when the rotor coils are lined up with corresponding stator coils. In operation, the synchro differential acts as an "electrical valve", through the coupling of its rotor to stator brought about by the positioning of the rotor shaft. If we use our symbols and diagram a synchro differential transmitter and a synchro differential receiver, we will have a quick means of indicating their functions and their differences.





Another way of indicating difference is to tabulate the data like this:

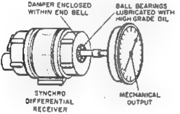
COMPARISON

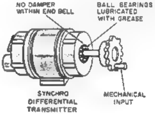
SYNCHRO UNIT	INPUTS	OUTPUT
Differential Transmitter	Synchro Signal and Mechanical	Synchro Signal
Differential Receiver	Synchro Signal and Synchro Signal	Mechanical

DIFFERENTIALS

TYPES OF DIFFERENTIALS

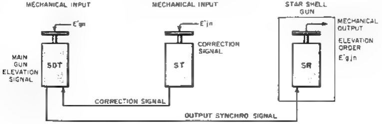
We found synchro transmitters and synchro receivers were the same electrically, the difference being in their applications. This similarity also applies to the synchro differential, for there are synchro differential transmitters and synchro differential receivers. A synchro differential transmitter is always used in a position where its shaft is driven by some large unit, so no damper is required. As a driven unit, the bearings are often grease-lubricated since friction is not critically important. A synchro differential receiver is used in a position where its shaft drives something (an indicator, a dial, or a switch) so a damper is a definite requirement. Their shafts must be prevented from spinning, "taking off", or oscillating. Friction being a critical factor because of accuracy requirements, the shafts are mounted on ball bearings and lubricated with the highest grade of light oil. Outwardly the synchro differential receiver and the synchro differential transmitter look alike. The receiver has a damper enclosed within its end bell, but, because of the typical sealed construction, it is not visible.





TYPICAL USE FOR SYNCHRO DIFFERENTIAL TRANSMITTER

An example of the use of a synchro team, using a differential transmitter, is found in star shell fire. The main gun elevation is computed, the data mechanically cranked into the synchro differential transmitter as E'gn. Correction signal E'jn is sent by the synchro transmitter and the values make up the output signal transmitted to the synchro receiver at the gun as elevation order E'gin. The gun can be elevated independently of the director when optical elevating or manual operation are deemed advisable, and switched to director control when required.



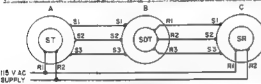
SYNCHRO DIFFERENTIALS

RULES FOR SYNCHRO DIFFERENTIAL TRANSMITTER WITH VARIOUS CONNECTIONS

All the connections that may be used in a standard synchro system involving a synchro differential transmitter are indicated below, with the corresponding relationship between shaft positions.

CONNECTIONS

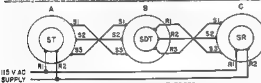
POSITIONS OF SR SHAFT (C) IN DEGREES, AS SHOWN BELOW:



DIRECT CONNECTED

1. Sum of inputs A & B if in opposite direction, C turning in same direction as A.

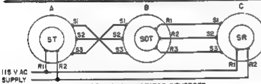
2. Difference between inputs A & B, if in same direction, C turning in same direction as A.



DIFFERENTIAL REVERSED

1. Sum of inputs A & B if in same direction, C turning in same direction as A.

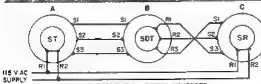
2. Difference between inputs A & B if in opposite directions, C turning in same direction as A.



DIFFERENTIAL STATOR REVERSED

1. Sum of inputs A & B if in same direction, C turning in opposite direction to A.

2. Difference between inputs A & B if in opposite directions, C turning in the opposite direction to A.



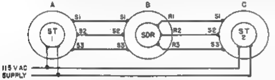
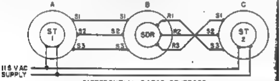
DIFFERENTIAL ROTOR REVERSED

1. Sum of inputs A & B if in opposite directions, C turning in opposite direction to A.

2. Difference between inputs A & B if in same direction, C turning in opposite direction to A.

RULES FOR SYNCHRO DIFFERENTIAL RECEIVER WITH STRAIGHT OR REVERSE ROTOR WIRING

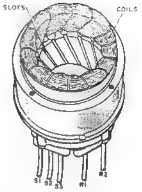
The relationships between shaft positions of a synchro differential receiver and a pair of synchro transmitters, when the differential rotor is wired straight or reversed to the second transmitter, are indicated below:

CONNECTIONS	POSITIONS OF SDR SHAFT (B) IN DEGREES, AS SHOWN BELOW:
 DIRECT CONNECTED	1. If A & C turn in same direction, B will turn in reverse direction and indicate difference between A & C inputs. 2. If A & C turn in opposite directions, B will turn in same direction as A and indicate sum of A & C inputs.
 DIFFERENTIAL ROTOR REVERSED	1. If A & C turn in same direction, B will turn in same direction and indicate sum of A & C inputs. 2. If A & C turn in opposite directions, B will turn in same direction as C and indicate difference between A & C inputs.

SYNCHRO CONTROL TRANSFORMER

HOW IT IS BUILT

The stator of a synchro control transformer looks just about the same as the stators of other synchros, except its coils are wound with finer wire and have many turns so that the coils have a higher impedance.



STATOR

WHAT THE SYNCHRO CONTROL TRANSFORMER DOES

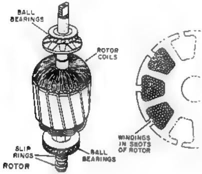
The synchro transmitter and synchro receiver, used as a team, offer a sensitive control where a mechanical output is required. Usefulness of this team is increased if a synchro differential (transmitter or receiver) is added, for the differential of the mechanical and electrical inputs can be used to control equipment. However, due to inherent inadequacies created by voltage variance and magnetic and friction losses, only moderate accuracy is provided. This moderate degree of accuracy is adequate for many applications, but where extreme accuracy is essential the differential team is avoided and replaced by a team comprised of a synchro transmitter and a synchro control transformer.

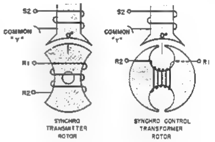
As the shafts of the synchro control transformer and the synchro transmitter are both turned by something, they are driven units. The synchro transmitter, powered by line current (E), sends out a synchro signal (S). The synchro control transformer receives a synchro signal (S) and gives a small variable AC voltage output.

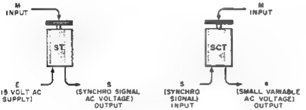
We can employ our symbols and use a diagram for the synchro control transformer and the synchro transmitter to obtain a visual comparison of their attributes, as:

While the rotor of the synchro control transformer looks very much like a synchro differential rotor, it is actually quite different. The coils are wound in slots but in place of being wired into three groups, the coils of the synchro control transformer are connected in series, with the two ends soldered to a pair of slip rings. The coils are wound with many turns of fine wire, the turns ratio being such that a maximum of 55 volts is induced in the rotor with normal stator voltage. As the rotor connections are never connected to the AC supply, the rotor does not induce voltage in the stator coils.

The synchro control transformer is built so that its "Electrical Zero" position is different from that of a synchro transmitter or synchro receiver. The diagram clearly shows the comparison between the two. On a synchro control transformer, the position where minimum voltage is induced in the rotor by coil number 2 (S2) is chosen as the electrical zero position. In this position the rotor coils act as if they were concentrated in one coil wound like this:







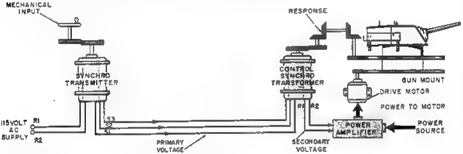
COMPARISON

SYNCHRO	INPUT	OUTPUT
Synchro Transmitter	Electrical (115 volt AC) Mechanical	Synchro Signal (AC voltage)
Synchro Control Transformer	Synchro Signal (AC voltage) Mechanical	Small Variable AC Voltage (e)

WHAT THE SYNCHRO CONTROL TRANSFORMER IS USED FOR

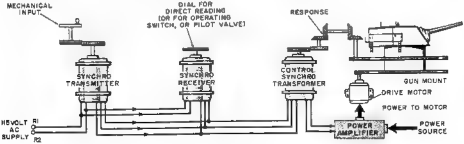
Assume a synchro team is required to train a gun and that a synchro transmitter will be used with a synchro control transformer for this purpose. The synchro transmitter rotor receives power from the AC supply. The operator will crank in, as a mechanical input, a particular setting. This will cause the synchro transmitter stator to transmit a specific primary voltage to the synchro control transformer stator and, in turn, induce secondary voltage in the rotor winding of the synchro control transformer. This secondary voltage, transmitted over leads R1 and R2, is used by the power amplifier to control the operation of the drive motor for the training of the gun. The gun mount, in turn, is geared to the rotor of the synchro control transformer to provide the mechanical response. When the rotor of the synchro control transformer has been turned by response to an amount equal to the signal from the synchro transmitter, the output voltage from the synchro control transformer drops to zero, and the signal to the amplifier ceases. This causes the power motor to cease operation. Thus the gun has been trained to correspond to the original signal cranked into the system.

In a similar manner a gun can be elevated or depressed, a searchlight directed, or similar equipment controlled, moved, or aimed. In practice, the rotation of the gun, or searchlight, can be regarded as simultaneous with the transmission of the signal. The synchro control transformer rotor is brought into correspondence within a fraction of a second after mechanical input to the synchro transmitter stops.



USING A SYNCHRO CONTROL TRANSFORMER AND A SYNCHRO RECEIVER ON THE SAME LINE

A synchro receiver can be added to a synchro control transformer system and wired so that it receives the same signals transmitted to the synchro control transformer. The synchro control transformer and the synchro receiver have separate positioning mechanisms. Rotation of the synchro control transformer rotor by the response has no effect upon the operation of the synchro receiver, since the position of the synchro control transformer rotor has practically no effect upon the currents that flow in the synchro control transformer stator coils. When the synchro control transformer rotor is turned by the response, there is no "kickback" to the system. Therefore, if power is shut off from the amplifier, and the gun, normally controlled by the synchro control transformer, is positioned manually, the resulting rotation of the synchro control transformer rotor will not affect other synchro control transformers or synchro receivers connected to the same line.



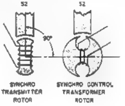
HOW THE SYNCHRO CONTROL TRANSFORMER WORKS

Stator current depends upon only the impedance of its windings, and is not appreciably affected by the rotor's position. There is no appreciable current in the rotor, nor does it tend to turn to any particular position when voltages are applied to the stator. Whatever the position of the rotor, the transformer rotor windings are so arranged that currents induced do not affect the currents that flow in the stator.

The transformer shaft is always turned by something, generally by response gearing from the mechanism being controlled, so that the variance in coupling will produce the required varying output voltages from the rotor winding. As it is a driven unit, it requires no internal damper. Because a synchro control transformer rotor does not turn in signalling a mechanism, rotor bearing friction does not affect the signal.

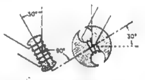
While the windings are wound equally around the rotor in slots, they act as if they were applied in a narrow band. A synchro transmitter rotor, in the 0° position lined up with stator coil S2 and the rotor of a synchro control transformer, also in the 0° position, may be diagrammed to show comparative coil effects, like this:

The rotor coils of the synchro control transformer act as though they were concentrated in one coil. On a synchro control transformer, the position where minimum voltage is induced in the rotor by coil S2 is chosen as the "electrical zero" position. Note that when the rotor coil of the synchro transmitter is in the "electrical zero" position, its coil lines up with stator S2, but when the rotor coil of a synchro control transformer is in zero position, its coil lies in a plane 90° to its stator coil, S2.

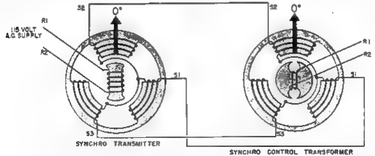


CORRESPONDENCE

When a synchro control transformer rotor coil lies at right angles to a synchro transmitter rotor coil, they are said to be in "correspondence". If the synchro transmitter rotor is moved 30° from its 0° position, the two rotors will be brought into correspondence if the synchro control transformer rotor is also moved 30°, bringing the rotor coils to a right angle with each other.



At the point of synchronism, the rotor of a synchro receiver takes a position which induces proper maximum voltages in its stator coils, equal to and opposite voltages produced by rotation of the synchro transmitter rotor. When the rotor of a synchro control transformer is turned by response until it is in correspondence with the rotor of the synchro transmitter, the voltage falls almost to zero. The hook-up of a synchro transmitter and a synchro control transformer in correspondence at 0° position, is like this:

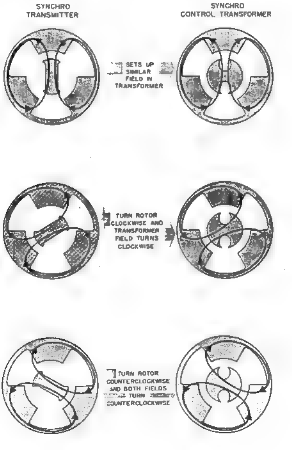


Note that the synchro control transformer rotor is NOT connected to the power supply; the leads carrying the small variable AC voltage generally go to a power amplifier. The power amplifier controls a power motor to position the gun or searchlight, and this equipment, in turn, is geared to rotor of the synchro control transformer to give a mechanical response.

HOW THE TRANSFORMER WORKS

MAGNETIC FIELDS

The magnetic field set up by the rotor of a synchro transmitter, when supplied with 115 volts AC, cuts the stator windings, and induces voltages which, transmitted to the synchro control transformer stator windings, induce a similar magnetic field. If the rotor of the synchro transmitter is turned clockwise, it causes the field to rotate in the same direction. Because the synchro control transformer field is set up by the synchro transmitter, the synchro control transformer field will turn clockwise by an equal amount. Rotating the synchro transmitter rotor counterclockwise causes both fields to rotate counterclockwise an equal amount. The synchro control transformer field movement depends upon the orientation of the synchro transmitter rotor, and will take place regardless of the position of the synchro control transformer rotor.



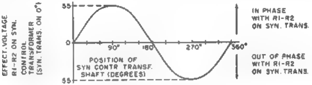
VOLTAGE OF ROTOR LEADS

With the synchro control transformer and synchro transmitter rotors in correspondence, a voltmeter will indicate almost zero. Actually there will be from 0.03 to 0.3 volt across the synchro control transformer leads, R1 and R2. In this position, lines of force (or flux) do not cut the coils, and only a minimum of voltage, due to small eddy currents, is produced. When the field is turned 10°, approximately 10 volts will be measured across the R1 and R2 leads. With the field turned 60°, voltage will be approximately 45 volts, while at 90°, voltage will be approximately 55 volts, the maximum voltage which can be induced in the transformer rotor winding. From this point (90°), continued turning of the field will result in decreasing voltage until, at 180°, the transformer output is minimum. At this point, the coils of the rotor winding are again parallel to the lines of force of the stator field, and the transformer rotor is again in correspondence.

Further turning will bring an increase in voltage until, at 270°, it will reach its maximum of 55 volts. At 360° (or 0°), output voltage is again at minimum. Thus, there are two points in the rotation of the field (0° and 180°) at which output voltage from the transformer rotor is at a minimum, and two points midway from these (90° and 270°) at which voltage is maximum. Rotating the field clockwise or counterclockwise from either the 0° or 180°, will give the same voltages, regardless of the direction in which the field is rotated.

Thus, when rotors ARE IN CORRESPONDENCE, there is a MINIMUM VOLTAGE across the synchro control transformer rotor leads. Minimum voltage is the lowest voltage obtainable; zero voltage is unattainable.

When rotors are NOT IN CORRESPONDENCE, there is MORE than minimum voltage across the synchro control transformer rotor leads, the amount depending upon the field position.



POLARITY OF ROTOR LEADS

Position of magnetic fields in relation to the rotor zero position determines the polarity of the synchro control transformer rotor leads. Polarity will change as the field is rotated through the two points of correspondence (0° and 180°) which lie 180° apart. At the 0° and 180° positions, the transformer rotor lies parallel to the path taken by the lines of force and, therefore, there will be no voltage across the synchro transformer rotor leads R1 and R2, and of course, no polarity.

Turning the synchro transmitter rotor clockwise from this 0° position will cause both fields to turn clockwise, and will cause a voltage to be set up across synchro control transformer rotor leads R1 and R2. If, at a given instant, polarity of this voltage is positive when the energizing voltage to the synchro transmitter rotor is positive, then synchro control transformer rotor lead R1 is plus when synchro transmitter rotor lead R1 is plus. This induced voltage across the synchro control transformer rotor leads is in phase with the AC supply to the synchro transmitter rotor.

When the synchro transmitter rotor is turned counterclockwise from the rotor 0° position, the voltage across synchro control transformer rotor leads R1 and R2 will be negative at the instant the energizing voltage applied to the synchro transmitter rotor is positive. Voltage from synchro control transformer rotor leads R1 and R2 will be 180° out of phase with the AC voltage from synchro transmitter rotor leads R1 and R2. The polarity of synchro control transformer rotor lead R1 is now minus when synchro transmitter rotor lead R1 is plus.

POLARITY VARIANCE

Polarity of synchro control transformer output voltage is determined by the position of the magnetic fields in relation to rotor 0° position. The output of a synchro control transformer is a voltage which varies in magnitude, and shifts polarity with the deviation of the synchro control transformer rotor from the position of correspondence. This output is a signal which can be amplified by means of a follow-up, and used to position mechanisms. We have found that when synchro control transformer stator coils are energized by the synchro transmitter, they merely induce voltage in the rotor, but do not turn it. It is this voltage, not rotor movement, which, transmitted to the amplifier, causes the drive motor to operate and thus provide motion to the mechanism.

TURNING SYNCHRO TRANSMITTER MOTOR

The turning of the synchro transmitter rotor causes four things to happen in the synchro control transformer:

1. The magnetic fields in the synchro transmitter and the synchro control transformer are caused to rotate

2. Voltages are induced in the synchro control transformer rotor

3. Polarity of the synchro control transformer rotor leads, with respect to voltage energizing the synchro transmitter rotor, becomes established

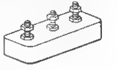
4. Response gearing rotates the synchro control transformer rotor toward the position of correspondence.

SYNCHRO CAPACITORS

HOW THEY ARE MADE

Synchro capacitors are designed to do only the job for which they are specifically intended. They are manufactured to exacting specifications and close tolerances, using the highest grade of paper and foil. After testing, three capacitors are selectively matched so they are individually within less than 1 percent value of each other. This matching is of particular importance because it affects current balance and must be correct if it [illegible] to keep the synchro system accurate. Total capacitance of the trio of capacitors forming the unit is held within 10 percent of rated value.

A typical navy standard synchro capacitor, consisting of the three matched capacitors sealed in a case, looks something like this:



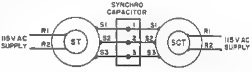
WHAT THE SYNCHRO CAPACITOR DOES

In subsequent electrical theory lessons, it will be brought out that electrical coils (whether they are coils in solenoids, relays, or synchros) are highly inductive and that current flow through them is comprised of what for convenience is called loss current and magnetizing current. The effective value of total current is somewhat less than the sum of these two values. Actually the role of the synchro capacitor is to cancel the magnetizing current, so that the line current, or current draw, will simply be the loss current of the coil.

USES FOR SYNCHRO CAPACITORS

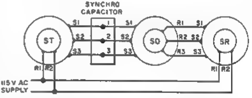
USING A SYNCHRO CAPACITOR WITH A SYNCHRO CONTROL TRANSFORMER

When the right synchro capacitor was added, the draw imposed upon a synchro transmitter by a synchro control transformer was reduced from 32 ma to 10 ma.



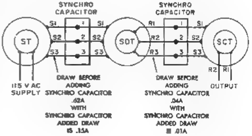
USING A SYNCHRO CAPACITOR IN A SYNCHRO TRANSMITTER, SYNCHRO DIFFERENTIAL, AND SYNCHRO RECEIVER SYSTEM.

Because the synchro differential draws current from the synchro transmitter and synchro receiver stators, their rotor currents are higher than normal. Since this current draw is largely magnetizing current, it can [illegible] greatly reduced by introducing the proper synchro capacitor across the synchro differential stator leads. By decreasing current draw, effective output is increased, resulting in better balance and decrease in synchro receiver current draw. Error in synchro receiver position is reduced by some [illegible] percent.

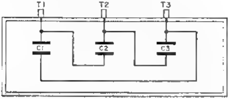


USING SYNCHRO CAPACITORS IN A SYNCHRO TRANSMITTER, SYNCHRO DIFFERENTIAL, AND SYNCHRO CONTROL TRANSFORMER SYSTEM.

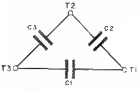
Both these associated units impose high current draw on the synchro transmitter. Proper capacitors will greatly reduce the load and provide greater system accuracy.



Internal wiring connects the capacitors (C) to the three terminals (T) in this manner:



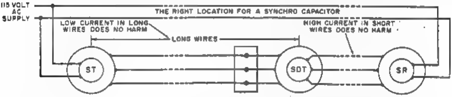
This delta connection may be shown this way:

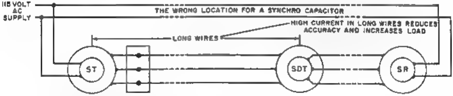


As a general rule, the AC generator supplying current to the synchro systems is of ample capacity for the job. There are cases where additional synchro teams have been added, or because of emergencies must be connected, so that the supply generator will be made to operate near, or at, its maximum capacity. In such cases it would be advantageous, or even essential, that synchro capacitors be installed to cancel the magnetizing current of the synchros and thus reduce the load on the generator. Furthermore, synchro capacitors increase system accuracy and reduce errors in synchro receiver positions.

LOCATING THE SYNCHRO CAPACITOR

A synchro capacitor must always be mounted close to the synchro differential or synchro control transformer for which it corrects current, otherwise its benefits may be lost.





IMPORTANT NOTES

Substitutes for synchro capacitors should not be used. Ordinary or commercial paper filter capacitors will cause high losses, result in unbalance, and destroy the system accuracy. Electrolytic capacitors can not be used, even for temporary replacement or test purposes, as they will immediately short circuit and may burn out the connected units.

Synchro capacitors should never be connected in the stator circuits between a synchro transmitter and a synchro receiver, as they would increase current draw and seriously reduce system accuracy.

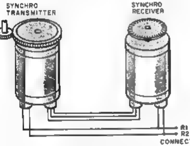
TRANSMISSION SPEEDS

DIFFERENCES IN DENOTING SPEEDS

In referring to synchro transmitters and synchro receivers, the terms "single-speed" and "double-speed" should not be confused with "one-speed" or "two-speed" transmission. Let us classify these terms.

SINGLE-SPEED TRANSMISSION

A single-speed transmission system, the simplest and least expensive, consists of a single synchro transmitter and a single synchro receiver, like this:



If we refer to the synchro transmitter of this system, we would call it a single-speed synchro transmitter, and call the receiver a single-speed synchro receiver.

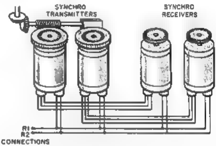
USE OF A SINGLE-SPEED SYSTEM

Because of low torque at the synchronizing point, bearing friction causes slight errors in the positioning of the synchro receiver in the single-speed transmission system. Such a system is sufficiently accurate to take care of quantities which have no definite reference, such as generated range or bearing. By use of gearing to transmit a small value per revolution, the transmission error can be reduced. For example, where a "change of range transmitter" is geared to transmit 100 yards of change per revolution, 1/2° of error in the position of the synchro receiver rotor will result in a transmitted error of less than 1 foot of range change. Quantities having a small range of values (for example, parallax corrections which are computed only between +12° and —12°) may be transmitted by the single-speed system. If one revolution of the synchro transmitter rotor represents, say, 25° of parallax, an error as large as 1/2° in rotor position will represent an error of only 2 minutes in the transmitted value.

A single-speed system can be made quite accurate by gearing the input, and transmitting a small value for each revolution of the synchro receiver dial.

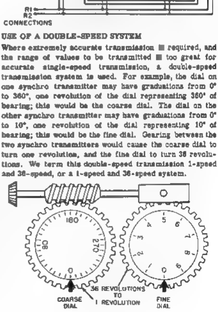
DOUBLE-SPEED TRANSMISSION

A double-speed transmission system consists of a pair of synchro transmitters, one coarse and one fine, geared together, and transmitting to one or more pairs of synchro receivers. The coarse dial synchro transmitter is usually worm-driven, and designed to rotate once for either 18 or 36 revolutions of the fine dial synchro transmitter. These two synchro transmitters, geared together as an integral unit, are termed a double-speed synchro transmitter, and the pair of synchro receivers is termed a double-speed synchro receiver.



USE OF A DOUBLE-SPEED SYSTEM

Where extremely accurate transmission is required, and the range of values to be transmitted is too great for accurate single-speed transmission, a double-speed transmission system is used. For example, the dial on one synchro transmitter may have graduations from 0° to 360°, one revolution of the dial representing 360° of bearing; this would be the coarse dial. The dial on the other synchro transmitter may have graduations from 0° to 10°, one revolution of the dial representing 10° of bearing; this would be the fine dial. Gearing between the two synchro transmitters would cause the coarse dial to turn one revolution, and the fine dial to turn 36 revolutions. We term this double-speed transmission 1-speed and 36-speed, or a 1-speed and 36-speed system.



1-SPEED AND 36-SPEED ASSEMBLY

DRIVING DIFFERENCES

OTHER RATIOS

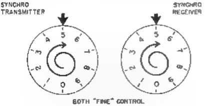
Where extremely accurate transmission is not required, the 1-speed and 18-speed system may be used; that is, where the coarse synchro transmitter turns once for 18 revolutions of the fine dial unit. For other applications, a 2-speed and 72-speed system may be used. In this case, each revolution of the coarse rotor represents 180° of bearing, so it turns twice to transmit 360 degrees. The fine dial is graduated into increments of 5°, leaving space between these major increments for finer graduations, to provide for accurate reading. Turning the fine dial 36 revolutions turns the coarse dial one revolution, representing 180° of bearing. The coarse dial is scribed to indicate 180°, and there is space between major increments for finer graduations.

INDICATING THE SYSTEM

One-speed transmission denotes a system in which a single speed represents one revolution of the transmitter rotor, and takes care of the entire range of values. A rotor representing 180° of bearing per revolution would have to turn two revolutions to transmit 360°, and would give 2-speed transmission. A rotor representing 10° per revolution gives 36-speed transmission. Double-speed transmission denotes a system in which two different speeds are used to increase accuracy. It involves two synchro transmitters with gearing between them which may drive, for example, at 1-speed and 36-speed, or at 2-speed and 72-speed.

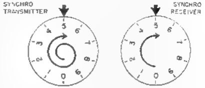
VALUE OF COARSE CONTROL

It might seem that a coarse control is superfluous, but actually it plays two important roles. For example, if we use a single-speed team of synchro transmitter and synchro receiver with dials graduated from 0° to 10°, we would have to turn the synchro transmitter rotor (and dial) 1-1/2 revolutions to crank in a value of 15. The numeral 5 would appear on each index. This same 5 would appear if we had cranked in 5, 15, 25, 35, etc.



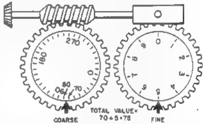
BOTH "FINE" CONTROL

With such a system, if the supply current is temporarily discontinued, and a value of 15 is then cranked into it, the synchro receiver dial would read 5 upon reestablishment of current. Its dial would make only 1/2 revolution, and not 1-1/2 revolutions. Human error and the possibility of temporary electrical failure make it impractical to read off total values from one dial to another after the completion of one revolution.



(1-1/2 REVOLUTION) (1/2 REVOLUTION)

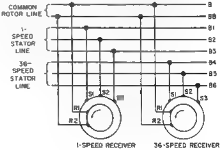
By using a coarse control with the fine control, accurate total values can be read from the dial. Total transmitted value can be read by adding the fine dial value to that of the lower of the two graduations indicated at the coarse dial index.



WIRING TWO-SPEED SYSTEM

In a synchro system where similar information is transmitted at several different speeds, more wiring is required than for a single-speed system. The two-speed hook-up uses three extra wires. The lowest speed wires of such a hook-up are marked 1, 2, and 3; while 4, 5, and 6 would be used to identify the next higher speed, like this:

CONNECTIONS ON TYPICAL TWO-SPEED SYSTEM



ZEROING SYNCHROS

ELECTRICAL ZERO

Synchros transmit or receive values by angular movement. A common reference point is needed, to which these units must be set before being connected in a system. In checking or setting synchros, electrical zero is used as the common reference point.

DIAL MARKINGS

When the shaft is at electrical zero, the reading to which a synchro receiver dial is set depends on its application. On a gun director train indicator system (and any other system which has "0" on its dial), the synchro dial is set to 0 for electrical zero. On a range transmission system, the dial is usually set to 1,000 yards; on a fuse time transmission system, it is set to 10 seconds. On an engine room telegraph system, an index mark at the center of the word STOP is used as zero position. Therefore, on any particular system, it is necessary to know the standard to be used for zero position.

ZERO READING AND ZERO POSITION

On synchro receivers, this zero position is called "zero reading", and the corresponding position of the synchro transmitter is called "zero position".

METHODS OF ZEROING SYNCHROS

There are several methods of zeroing or checking synchros, involving the use of an AC voltmeter, a standard synchro receiver, test lamps, head phones, and wire jumpers. The first two methods are acceptable; the latter are for rough or emergency checks.

Zeroing a synchro means, in general, adjusting it mechanically to coincide with the electrical zero position so it will work properly in a system in which all associated synchros are zeroed.

ELECTRICAL ZERO VOLTAGES

In the following description, the term "electrical zero" voltages means the voltages required to cause a synchro receiver to turn to electrical zero by application of 115 volts AC between lead R1 and lead R2, and having 78 volts in phase with leads R1-R2 between leads S2-S1 and S2-S3, and 0 volt between lead S1 and lead S3. Thus, a synchro receiver is zeroed if its dial shows the zero reading when electrical zero voltages are applied.

A bearing-mounted synchro receiver is zeroed if its dial reads zero when electrical zero voltages are applied, and the unit to which its stator is geared is set to zero position; or if it is a switching unit, its switch is centered between contacts.

A synchro transmitter is zeroed if it produces electrical zero voltages when the unit for which position is being transmitted is set to zero positon.

A synchro differential receiver is zeroed if its dial shows the zero reading when electrical zero voltages are applied to both its sets of windings.

A synchro differential transmitter is zeroed if its secondary (rotor) voltage is zero when electrical zero voltages are applied to its primary (stator) and the unit whose position it transmits is set to zero position.

A synchro control transformer is zeroed if its secondary (rotor) voltage is zero when electrical zero voltages are applied to its primary (stator), and the unit for which position is being transmitted is set to zero position; and if turning the control transformer shaft slightly counterclockwise produces a voltage from lead R1 and to lead R2 which is in phase with the voltage from lead R1 to lead R2 on the transmitter supplying its stator. The position where minimum voltage is induced in the rotor by stator coil 2 is chosen as electrical zero position.

PROBLEMS

1. Where are the inputs of a synchro transmitter, and what is its output?

2. Where are the inputs of a synchro receiver, and what is its output?

3. What effects do the lines of force set up by the rotor have on the voltage induced in the stator coil of a synchro transmitter?

4. When a synchro transmitter is in ELECTRICAL ZERO position, what is its setting?

5. What is meant by "standard synchro transmitter and synchro receiver hook-up"?

6. In the standard electrical hook-up, how do the synchro transmitter and synchro receiver shafts turn in relation to each other?

7. In a reverse hook-up, how is the synchro transmitter connected to the synchro receiver?

8. When synchros are electrically connected in reverse hook-up, in what direction does the synchro receiver shaft turn in relation to the synchro transmitter shaft?

9. In a multiple system where one large synchro transmitter is used to drive a number of small synchro receivers, why is it essential for the receivers to have identical loads?

10. If a synchro receiver has the proper capacity, could it be used in an emergency to replace a defective synchro transmitter? Explain.

11. Explain what would happen in the case of a synchro transmitter used in an emergency to replace a synchro receiver of the same size?

12. On a synchro differential, how many stator leads and how many rotor leads are there?

13. What are the inputs to a synchro differential transmitter, and what does it deliver?

14. What are the inputs to a synchro differential receiver, and what does it deliver?

15. In the above system, supposing that it was essential for the rotor of the synchro receiver to deliver an output in the reverse direction; draw a diagram of the system which would provide this delivery.

16. What is the output of a synchro control transformer?

17. What connections are made to synchro control transformer rotor leads?

18. Explain the position of the rotor of a synchro control transformer when it is in CORRESPONDENCE with its associated synchro transmitter.

19. What comprises the standard synchro capacitor?

20. What synchros benefit by use of synchro capacitors?

21. When adding a synchro capacitor to a system, where should it be located?

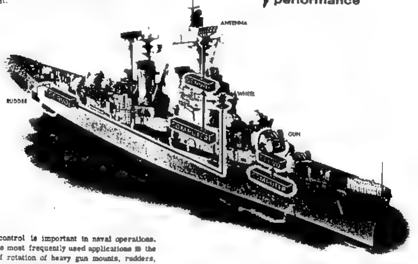
Introduction to

SERVOS

CHAPTER 4

The problem of control is common in every day life. We speak of controlling an automobile, controlling the volume of a radio set, or controlling the temperature of a house. In fact, picking up a pencil involves control of muscles in a way similar to guiding a missile to a target.

- principles
- components
- performance



Precise control is important in naval operations. One of the most frequently used applications is the control of rotation of heavy gun mounts, rudders, or antennas to correspond to ordered positions, as shown on indicators or computer dials.

A servo system is no more than a system of control. Servos are devices designed to transfer an order, which may come from another mechanism, or a human being, into a rapid and accurate physical operation.

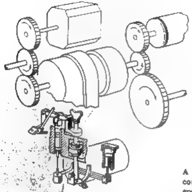
Orders may be represented by dial readings, pointer index positions, or switch positions. The functions performed by a servo system may include movements of objects, temperature regulation, and color changes.

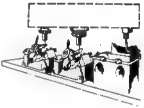
SCOPE OF THIS CHAPTER

The chapter is divided into three sections. The first section explains the principles of servos by means of typical examples of basic types of servos. The meaning of stability is discussed, and a few ways of improving stability are studied. The second section covers some specific components used in servos. This gives the student a practical acquaintance with the equipment. The third section discusses the accuracy of servos, and methods of improving servo accuracy.

SECTION 1

PRINCIPLES OF SERVOS





A servo is composed of various components, each performing a specific function. The combination of these functions determines the overall operation of the servo. In this section, principles of the overall servo system are discussed. In the following section, individual components which determine the system operation are covered.

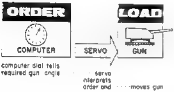
scope of section

The principles of servos are discussed by considering the operation of basic systems — manual and automatic. The principles of on-off control, and variable control, introduce the idea of servo stability. Then, modifications to the basic servo for the improvement of stability are discussed.

BASIC MANUAL SERVO

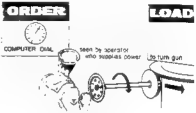
A SERVO PROBLEM

One of the many types of problems which a servo may be required to solve is the movement of a heavy gun mount in response to an order generated by a computer, and indicated by the reading on the dial.



A SIMPLE SOLUTION

The simplest type of servo which will solve a problem like this is the manual servo. This type consists of a man reading the computer dial and turning the gun mount by hand until the mount position is the same as the ordered position.



BASIC AUTOMATIC SERVO

need for automatic servo . . . .

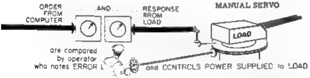
making servo automatic

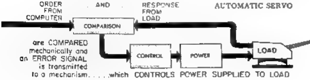
The necessary speed and accuracy for modern servo use can be attained by mechanization. In order to mechanize a manual servo, we must mechanically duplicate each manual function.

These functions, whether performed manually, or automatically, are essential in any servo, and may be considered as the basic principles of all servos.

1. COMPARISON of order and response to determine error.
2. CONTROL of power by the error.

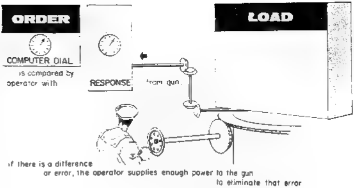
In a manual servo, these functions are performed by the operator. In an automatic servo, they are performed by mechanisms.





The specific devices used as components to fill these "black boxes" can take many forms. The function of the comparison device is to subtract the response from the order. A differential can accomplish the required subtraction. The power supply may be a motor, controlled by the error, through a switch.

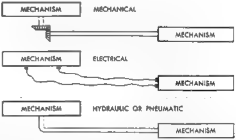
To position the gun mount accurately, the operator will need an indicator to show him the exact present position of the mount. Such an indicator may be a simple dial. The reading on the dial is called the response of the gun. The difference between order and response is called error.



Although the Basic Manual Servo is simple compared to the complicated servos found on a modern ship, nevertheless, it has all the essential properties of a servo.

The manual servo does not have the necessary speed and accuracy for many servo applications. A heavy object such as a gun mount can [redacted] best controlled by an automatic servo with a source of high power.

TRANSFER OF SIGNALS



The devices contained in the "black boxes" need not take a mechanical form. It is very common to have servos which operate electrically, hydraulically or pneumatically.

Signals may [redacted] transferred from one mechanism to another by any of these means.

SUMMARY

The order and response signals of a servo need not be mechanical. For example, servos using the same principles as discussed here may control such diverse quantities as missile direction, height of water in a tank, machine shop operations, pressure and temperature. In fact, the household thermostat is a common form of automatic servo.

Both the Basic Manual and Basic Automatic Servos function according [redacted] the same principles. These principles apply to all servos discussed in this chapter.

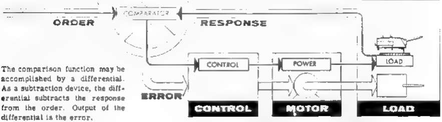
They are: comparison of order and response to determine error; and control of power by error.

ON-OFF CONTROL SERVO

mechanization of servo functions

One of the simplest types of automatic servo is the on-off control servo. In order that we may consider a completely mechanical servo, let us assume that the comparison and the control are accomplished mechanically.

Differential as comparator



The comparison function may be accomplished by a differential. As a subtraction device, the differential subtracts the response from the order. Output of the differential is the error.

The control is the device which takes the error and converts it into a signal to the power supply, which may be an electric motor. The control function is important, and will be discussed in some detail.

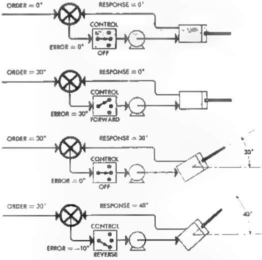
operation of an on-off control servo

Assume that, initially, the load is at its zero position, and the order (from the computer) is zero. At this point, the error is zero, and the control is in the off position.

Suppose that suddenly the order is changed to 30 degrees. Since the order no longer equals the response, the error will turn the control to the forward position, and the motor torque will accelerate the load.

As the load accelerates, the error is reduced until the load position is also 30 degrees. At this point, the error is again zero, and the motor is turned off. However, merely turning off the motor does not stop the load. If the load has nothing to brake it, it will continue to coast past the desired value of 30 degrees.

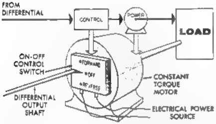
At this point, the negative error turns the control to reverse, and the negative torque decelerates the load, causing it to stop and return toward the desired value. However, again the load may coast past the desired value, this time in the opposite direction.



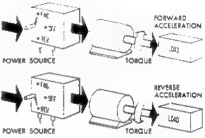
The tendency of the load to overshoot the desired value is a common hindrance to efficient servo operation. Therefore, it deserves further study.

the on-off control

One way of mechanizing the control function is by a switch. This switch must be constructed so it can be operated by the differential. When the error is zero (order equals response), the switch is "off". When the error is positive (order greater than response), the switch is on "forward". When the error is negative (response greater than order), the switch is on "reverse".

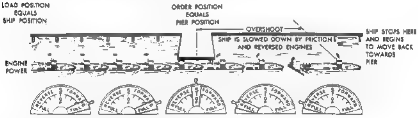


The motor, controlled by the switch, gives the load constant torque, operating either forward or reverse. This torque serves to accelerate the load in the direction of the torque.

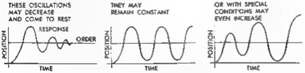


overshoot

When the load position overshoots the order position, this action is comparable to a ship approaching a pier, and stopping its engines only when it comes alongside the pier.



Overshoot may be repeated every time the load approaches the order, thus, causing the system to oscillate about the ordered position.



A system with oscillations which decrease with time, is said to be stable.

A system with oscillations which remain the same or increase, is said to be unstable.

SUMMARY

The use of an on-off switch is one way to mechanize the control of servos; other types of servo controls are often used. Advantages of the on-off control are its simplicity and reaction speed. A disadvantage is its poor stability.

VARIABLE SPEED CONTROL SERVO

need for variable control

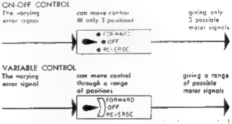
One reason for the instability of the on-off control is the fact that, as the load approaches the desired value, the torque exerted by the motor remains constant. This high torque tends to drive the load past the desired value.

A more stable servo would be one which reduces the torque gradually as the load response approaches the value of the order. Use of a variable control is one way to achieve such increase of stability.

variable control

The on-off control responds to the presence of an error by giving a constant signal to the motor. The variable control responds to the degree of error, and gives a signal to the motor proportional to the error.

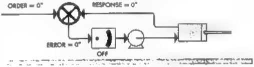
Thus, for large errors, when the order is much greater or less than the response, a strong signal will be sent to the motor. For small errors, when the response is catching up to the order, the signal to the motor will be weak.



The on-off control servo provides constant torque for any error.
The variable control servo provides torque proportional ■ the error.

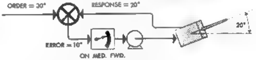
operation of variable control

Suppose, as before, that the order and response are originally in their zero positions. Again, the error is zero, and the motor is off.

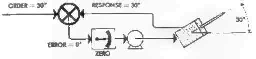


Just as with an on-off control, when the order is suddenly changed to 30 degrees, the error will give a strong signal to the motor, and the motor torque will accelerate the load.

However, with a variable control, as the load approaches the desired position, the error gives a continually weaker signal to the motor and the torque is gradually decreased. The decreased torque allows the load to slow down before reaching 30 degrees.



Slow moving load will not tend to overshoot as much as fast moving load of on-off servo.



The manner in which the overshoot of the variable control servo differs from that of the on-off control servo will be further illustrated.

requirements of variable control

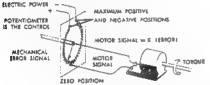
The purpose of the variable control is to provide a motor signal proportional to the error signal. The relationship:

motor signal = K (error)

must hold for a simple variable control. Many devices fulfill this requirement.

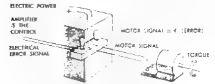
POTENTIOMETER

The potentiometer is one such device. It can be considered as a switch which has a variable, rather than an on-off, characteristic.



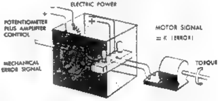
AMPLIFIER

When the error signal is electrical, a simple amplifier may be sufficient to give the proper motor signal.



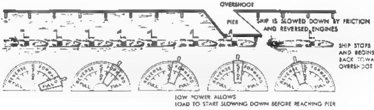
POTENTIOMETER PLUS AMPLIFIER

In some cases, an amplifier and potentiometer may be used together.



overshoot

The effect of reducing the torque as the error is reduced can be clearly seen if we reconsider the illustration of the ship approaching a pier. As the ship approaches (decreasing error), power is reduced by degrees. Consequently, the overshoot is smaller.



SUMMARY

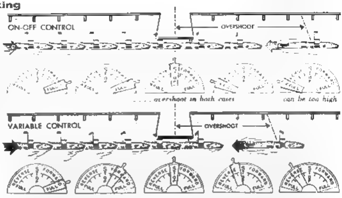
The variable control servo is more stable, but is less simple and slower to respond to sudden changes, than an on-off servo. Although we have treated the order as being constant, in operation the order might be changing continuously. In general, if the order is expected to change, load must be capable of moving as fast as the order is expected to move. It is the control and power supply which determine the way in which the load will follow the order.

STABILIZING A SERVO

the effect of braking

Although a servo having variable control is more stable than one with on-off control, normally both will overshoot. Consider the illustration of a ship approaching a pier.

With on-off and variable control, only friction between the ship and the water slows it down.



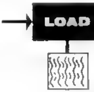
braking force constant

ADDING FRICTION

In a servo system there is always some dry friction. The friction can be increased if it is necessary for stability.

Dry friction force is constant, and it always opposes the motion of the load.

When power is low, and constant friction force is greater than power applied, the load decelerates.

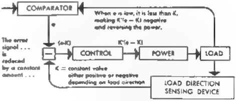


Examples of devices for applying dry friction (brakes) are discussed in the following section.

Dry friction applied to load

REVERSING POWER

The same effect may be obtained by reversing the power. To do this, the error signal e, is reduced by a constant amount K. As the error signal becomes low, K will be greater than e. The signal becomes negative, reverses the power, and decelerates the load.

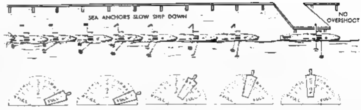


The signal by which the error is reduced always tends to decrease load motion, just as friction always tends to decrease load motion. When the load is moving forward, K will be positive. When the load is moving in reverse, K will be negative. Some sort of device is necessary to sense load direction and to transmit a constant value which has sign value depending upon that direction.

there are two basic ways to eliminate high overshoot
by adding friction and by reversing the power

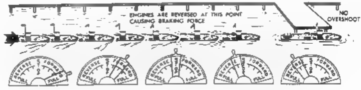
ADDING FRICTION

One way of eliminating overshoot is to apply more friction to the load. A ship might do this by use of a sea anchor; but, this is usually impractical.



REVERSING POWER

Another way to eliminate overshoot is to reverse the power (engines) before reaching the pier.

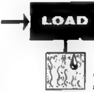


braking force dependent on speed

ADDING FRICTION

In a servo system there is always some wet friction (proportional to speed), such as air and water resistance, and lubricated friction.

Wet friction has the advantage of being small when the load is moving slowly (requiring little decelerating force), and large when the load is moving fast (therefore requiring a large decelerating force).



Like dry friction, wet friction always opposes the motion of the load.

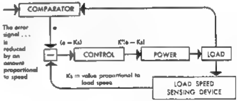
Wet friction *(proportional to speed)* applied to load

REVERSING POWER

The same effect may be achieved by reversing power, instead of increasing wet friction.

In the duplication of dry friction, the error was reduced by a constant amount. In order to duplicate the effect of wet friction, the error must be reduced by an amount proportional to load speed.

To reduce the error by an amount proportional to load speed, a device sensitive to load speed must be used. Reducing the error in this manner is called negative rate feedback.



When e is low, and speed s is high, K'(e-Ks) is negative. It acts opposite to the original error signal. This negative signal will reverse the power, and prevent the load from coasting beyond the value ordered.

SUMMARY

The amount of braking in a servo is called the damping of the servo. If there is just enough braking to eliminate oscillations, the servo is said to be critically damped. If there is more or less than this critical value of braking, the system is overdamped or underdamped.

SPECIAL TYPES OF SERVOS

non-linear control

In the servos studied in this chapter, the control performed the function:

motor signal = K (error)

This relationship is linear.

Actually, the motor signal may be any function of the error. For instance, a control may be designed so that:

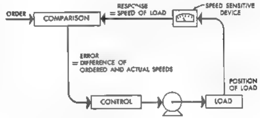
motor signal = K $(error)^2$.

This would give a larger motor signal than usual for large errors

This flexibility gives servos a wide range of uses. By a system of servos, an aircraft could take off in New York, fly across the Atlantic, and land in London, all automatically.

position and velocity servos

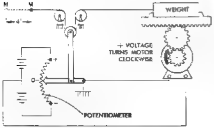
The function of all servos studied so far, is to have the position of the load equal to the position of the order. The error is then an indication of a position difference. These are called position servos. In a velocity servo, the velocity of the load (not its position) is compared with the order. The error exists until the velocity of the load is at an ordered value. This type of servo can be made to move the load constantly at a desired velocity by a single setting of the order shaft.

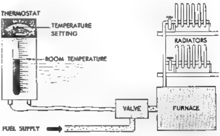


PROBLEMS

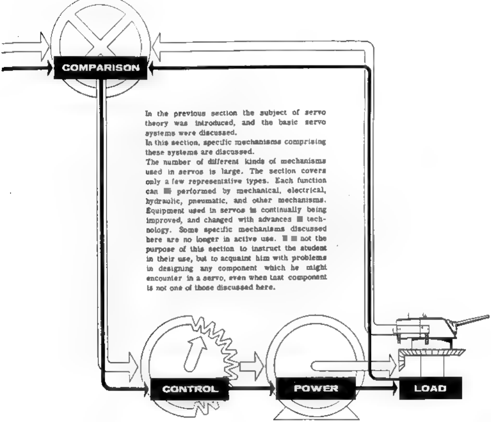
What happens in the system shown, as cable M is moved left four inches? Show how this is a servo, by drawing a schematic diagram of a variable control servo, and locating corresponding functions in the system shown.

The thermostatic operation of a furnace is a form of servo. Describe this operation in terms of order, response, comparison, control, power, and load.





COMPONENTS OF SERVOS



In the previous section the subject of servo theory was introduced, and the basic servo systems were discussed.

In this section, specific mechanisms comprising these systems are discussed.

The number of different kinds of mechanisms used in servos is large. The section covers only a few representative types. Each function can [redacted] performed by mechanical, electrical, hydraulic, pneumatic, and other mechanisms. Equipment used in servos [redacted] continually being improved, and changed with advances [redacted] technology. Some specific mechanisms discussed here are no longer in active use. [redacted] [redacted] not the purpose of this section to instruct the student in their use, but to acquaint him with problems in designing any component which he might encounter in a servo, even when that component is not one of those discussed here.

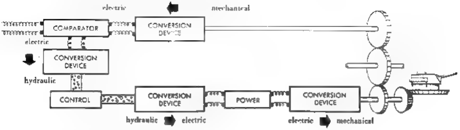
scope of section

In the previous section, each function was carried out by a mechanism. Mechanisms were discussed briefly in order to concentrate on the functions they performed. In this section, the mechanisms are discussed in more detail. The function of conversion is introduced. The functions of comparison, control, speed measurement, friction and inertia are covered. Power is usually assumed to be supplied by an electric motor and is not discussed separately. However, power may be of other forms. It is the control of this power with which the servo is concerned.

CONVERSION

purpose of conversion devices

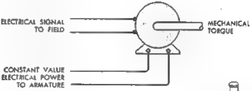
Within one servo system, electrical, mechanical and hydraulic devices are often used together.

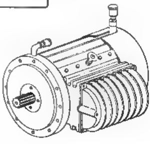


In such a system, it is necessary to convert one type of energy to another type. To do this, devices are required to accept an input of one type of energy, and deliver an output of another type which will be proportional to the input.

electrical to mechanical

A device commonly employed to convert electrical energy to mechanical energy is the electric motor.





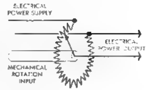
POWER DRIVE MOTOR

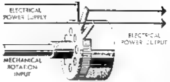
Motors used as power devices in servo systems perform a conversion function.

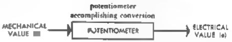
DEVICES

mechanical to electrical

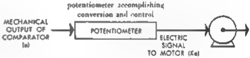
We have ascertained that the potentiometer may be used as a control. We may also utilize the potentiometer for conversion. The input to the potentiometer is mechanical, and the output is electrical.





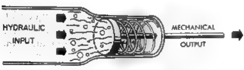


Many devices are capable of performing more than one function. A potentiometer may be used simply as a conversion device, or as a control which also performs the function of conversion.



hydraulic to mechanical

A device which converts pressure of a fluid to mechanical motion is the piston and cylinder.



note

In a sense, any device in which the output is of a different type of energy than the input is a conversion device.

For instance, the comparator may compare a mechanical signal with an electrical signal, and produce a hydraulic error.

In this section, a device will be considered a conversion device only if its primary function, in the servo under consideration, is conversion.

SUMMARY

Conversion devices, such as the piston and cylinder, convert one kind of energy directly to another. Others, such as the potentiometer, require a supply of constant power. In both cases, the output is a different kind of energy than the input, and is proportional to the input.

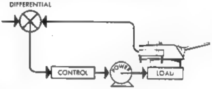
COMPARATORS

purpose of comparators . . . .

mechanical

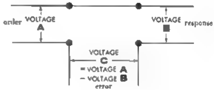
One device which mechanically performs a comparison function is the differential. The operation of subtraction as performed by a differential is the same as the operation of comparison.

The differential is so commonly used as a comparison device that the symbol for the differential is often used to represent any comparison device.



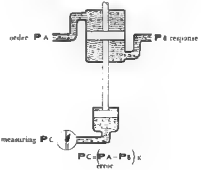
electrical

Electrical comparison is accomplished by the simple connection of a pair of leads. The two leads are arranged so that the voltages to be compared will oppose each other. The resulting voltage is their difference.

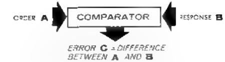


hydraulic

The following arrangement is only one of many possible ways to compare two hydraulic values.

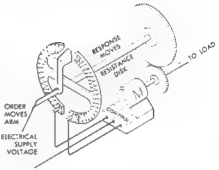


As with the other devices studied in this section, we will cover only a few typical comparators. Every comparator has two inputs, and an output which is some function of their difference. One input is the order, and the other is the response. The output is the error.

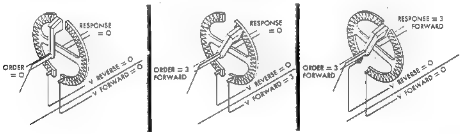


electro-mechanical

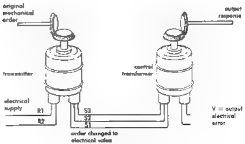
The following device can receive two mechanical inputs, and deliver an electrical output. Like the potentiometer, it requires an electrical supply voltage. This device combines the functions of comparison and conversion.



Assume conversion factor
=1 between electrical and mechanical quantities.



The synchro control transformer may act as a comparison device.
The order is originally mechanical. The transmitter acts as a conversion device and makes it electrical. The electrical signal is transferred to the stator windings of the control transformer and the mechanical response signal is applied to the rotor. The output voltage taken from the rotor is the difference between them.



note The output voltage may be used directly as a motor signal, or modified further. When voltage is used as a motor signal, the combined functions of comparison and control can be regarded as performed by an electro-mechanical device.

CONTROLS

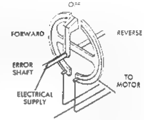
purpose of controls

The purpose of the control is to convert the error signal to a proper motor signal. Accomplishing this purpose might involve conversion, amplification, reduction of the error signal, or a combination of these functions.

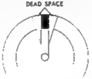
ON-OFF CONTROL

mechanical-electrical

On-off controls can be considered as switches. The most common switches have mechanical inputs and electrical outputs. One such switch is the rotary switch. The arm makes contact with either of two metal contacts, one of them connected to the forward terminal of the motor, and one to the reverse terminal.



The above switch needs some small error signal before making contact. The small amount of play in the error shaft is called "dead space". This delays reaction time, and decreases accuracy. It is undesirable, but, in such mechanisms, is unavoidable.

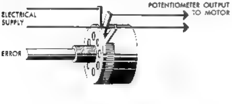


Mechanical switches must allow the error shaft freedom to turn and to maintain contact at the same time. The rotary switch allows almost 160 degrees of rotation before losing contact.

VARIABLE CONTROLS

mechanical-electrical

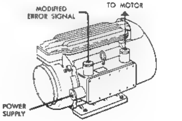
A variable control can be considered a switch with the ability to change gradually from zero to maximum signal. The use of the potentiometer as a variable control is exactly the same as its use as a converter. The only difference is that when considered as a control, the potentiometer output is used as the motor signal.



As seen in the section on Servo Principles, a potentiometer and amplifier may be combined.

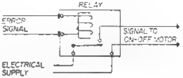
electrical-electrical

When the error signal is electrical, the control function can be accomplished by an amplifier. The amplifier may be electronic, or may be an amplidyne motor-generator, a form of amplifier having easily controlled amplification characteristics. In certain cases, an amplifier and an amplidyne unit are used together.



The control must supply a motor signal of sufficient strength without requiring too much power (error signal) from the comparator, which is an accurate, delicate instrument. The type of control determines many characteristics of servo operation.

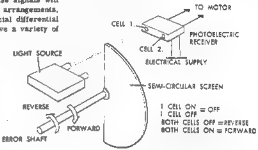
electrical-electrical



A switch may have an electrical input and output. Such a switch is a relay. In the relay, the input current energizes an electromagnet closing a contact. The minimum current necessary to move the contact is like dead space in a mechanical switch. As shown, the relay control gives the same motor signal for both positive and negative error signals. Thus, reverse signals will not ordinarily be obtainable. However, by special arrangements, coded signals in the form of pulses from a special differential can be made to trigger a series of relays to give a variety of motor signals.

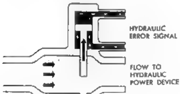
others

There are many other kinds of switches. One device which can be considered as a switch is a photocell. An advantage of the photocell is that it puts practically no load on the comparator. This permits the use of a very sensitive and accurate comparator.



hydraulic-hydraulic

Another type of variable control common in naval use is the hydraulic control.



note

The output of the control divided by its input is called the gain. If amplification is accomplished by the control, the gain will be greater than unity. A control with a high gain will have the desirable characteristic of low load on the comparator, and high signal to the motor. Some undesirable characteristics of high gain will be discussed in the following section.

SUMMARY

The purpose of a control is to convert the error signal from the comparator into the appropriate motor signal. This may involve conversion, amplification, or both. Each control has some gain. The gain is determined by dividing output by input, after both have been converted to the same units of measurement.

SPEED SENSITIVE DEVICES

purpose of speed sensitive devices

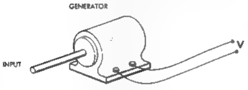
The purpose of the speed sensitive device is to produce an output proportional to the input speed.

Direct speed sensitive devices are called TACHOMETERS

Speed sensitive devices were discussed in detail in the section on Rate Measurement.

mechanical-electrical

One type of speed measurement device often used in servos is the generator.



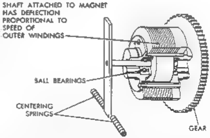
Voltage proportional to speed of input

mechanical-mechanical

A speed sensitive device with a mechanical input and output is sometimes desired in a servo. One such device is the magnetic drag.

The input turns the gear to which the outer windings of wire are attached. The rotation of these windings through the field of the magnet sets up currents in the wire. These currents, in turn, set up a magnetic field; this field tends to pull or "drag" the magnet along with the windings. The magnet is restrained by the spring. Forces involved are such that the rotation of the magnet allowed by the spring is in proportion to the speed of the outer windings.

Another device, called the hydraulic drag, works on a similar principle. The dragging force is provided by liquid viscosity instead of a magnetic field.



electrical-electrical

It was pointed out in the Rate Measurement section that, since the output of a speed sensitive device is the derivative of the input, the device can be considered to be a differentiator.

Electronic differentiators used in electrical servos may be made to perform the same function as tachometers in a mechanical servo.

FRICTIONAL AND INERTIAL DEVICES

purpose of frictional and inertial devices

Friction and inertia are present in any system. It is often necessary or desirable to control them. This control can be accomplished by the use of devices discussed here.

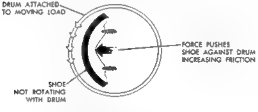
friction devices

Friction devices are called dampers. The amount of friction (dry and wet) in a system determines how much it is damped.

Dry friction can be increased by sliding devices, such as brakes and clutches and reduced with lubricants, and ball bearings.

The speed measuring devices which produce a force proportional to speed (magnetic and hydraulic drags) can be used as dampers, supplying wet friction — friction proportional to speed.

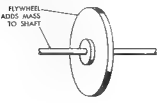
In an electrical system wire resistance acts in a manner similar to dry friction in a mechanical system. Dry friction reduces speed. Wire resistance reduces voltage. It remains the same as AC frequency changes. Capacitance acts similarly to wet friction. Changing AC frequency changes capacitive reactance.



inertial devices

Inertia can be increased by adding mass to the load. A specific device used to add mass to a load shaft is the flywheel. The high inertia of the flywheel prevents small fluctuations from disturbing the load. Inertia may be reduced by reducing the mass of the load.

In an electrical system, an inductance in series acts similar to inertia in a mechanical system.

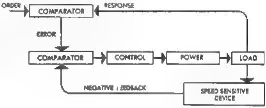


DESIGN OF A SERVO SYSTEM

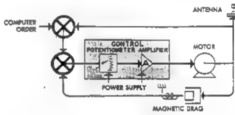
In designing any servo system, there are three decisions to be made:

1. What components are needed to perform the required functions?
2. What type of mechanisms shall be chosen to perform those functions?
3. How shall mechanisms be arranged and connected to perform correctly?

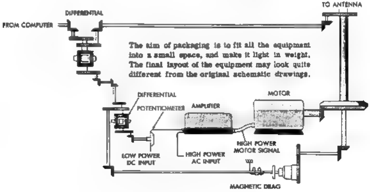
Suppose that a computer supplies a signal which is to be used to position an antenna. Assume that the type of servo best suited to the job is the simple position control servo having negative rate feedback, as shown to the right. (The next section will explain some reasons for choosing one type of servo instead of another.)



After this choice has been made, the black boxes indicating the functions must be replaced by indications of the actual equipment to be used. The servo must then be designed, and values of components must be calculated. For instance, the voltage characteristics and torque characteristics of the motor, the size of differentials, gear ratios, and specifications for all equipment must be determined. The methods for making such calculations are complicated, and are not within the scope of this book.



Finally, the equipment must be connected and "packaged".

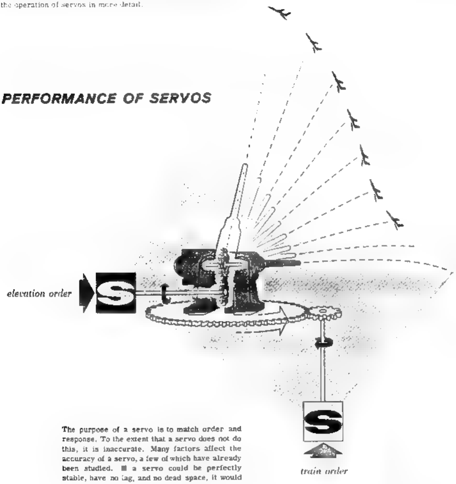


The aim of packaging is to fit all the equipment into a small space, and make it light in weight. The final layout of the equipment may look quite different from the original schematic drawings.

SECTION 3

The first two sections in the chapter on servos introduced the student to the subject, and familiarized him with the components of servo systems. The present section covers the operation of servos in more detail.

PERFORMANCE OF SERVOS



The purpose of a servo is to match order and response. To the extent that a servo does not do this, it is inaccurate. Many factors affect the accuracy of a servo, a few of which have already been studied. If a servo could be perfectly stable, have no lag, and no dead space, it would be perfectly accurate.

SCOPE OF SECTION

We will investigate, one by one, the important factors which affect the accuracy of a servo. These are, stability, dead space, and lag. Then, we will study mathematical analysis of servo performance, and a method, called frequency response, by which servos may be evaluated.

STABILITY . . . .

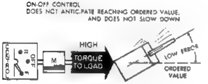
EFFECT OF CONTROL ON STABILITY

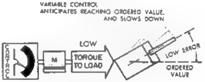
on-off control

. . . tends to be unstable because it does not have "anticipation". The on-off control acts similarly to a ship in which the engine is not stopped until it reaches a pier, and consequently drifts past it.

variable control

. . . tends to be more stable than the on-off control. It anticipates a condition of zero error by reducing the power before the error is zero, allowing friction to slow down the load.





IMPROVEMENT OF STABILITY

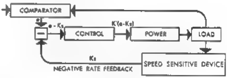
controlling friction

One way to improve stability is by increasing friction. High friction reduces overshoot, and thereby reduces the oscillations.

As discussed in the section on Principles, friction is generally considered as composed of two types, dry, and wet. Dry friction is constant for changing load speeds. Wet friction increases as load speed increases.

The disadvantage of increasing friction as a method of improving stability is that the resistance of the load to motion is increased, thereby increasing the reaction time. To get the same reaction time, and the same general response characteristics, the power supply must be increased.

reversing power



Reversing power by means of negative rate feedback will improve stability in the same manner that friction will improve stability.

Negative rate feedback reduces load speed indirectly by reducing power, rather than directly, as friction does, by increasing the load. Since negative rate feedback does not increase load friction, it uses less power and, for that reason, requires a smaller power supply.

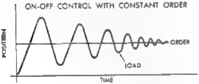
A disadvantage of negative rate feedback is the increased complexity and the cost of equipment involved in its use.

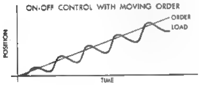
Stability is a measure of the number and magnitude of oscillations of the load about an ordered value. A servo may be stable for some values, and unstable for others. The type of control affects stability.

STABILITY WITH MOVING INPUT

on-off control

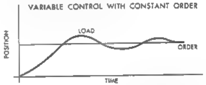
. . . cannot follow a moving order signal continuously. When the response equals the order, the motor shuts off. If the order is constantly increasing, the load will repeatedly catch up to the order, stop, fall behind, start, catch up, stop, fall behind, etc. Only when the order has stopped moving can the response continue to be equal to the order.

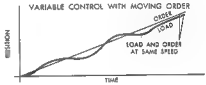




variable control

. . . can adjust the torque of the motor so that the load will move at the same speed as the order. After the preliminary oscillations have died down, the load moves smoothly at the same speed as the order, not constantly catching up and falling behind as it would when an on-off control is used.

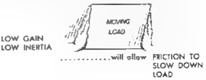




controlling inertia and gain

Although friction (or its equivalent) reduces oscillations, the inertia of the load and gain of the system influence the effect of friction. For instance, if the system has high gain (high motor torque for low error), or high inertia (heavy load to move), friction will have to be very high in order to slow down the load, and to decrease oscillations. However, if gain is low, and inertia is low, a small amount of friction will be sufficient to slow down the load, and to keep oscillations low.

Gain can be controlled by either increasing or decreasing amplification. Inertia may be controlled by increasing or decreasing the weight of the load.

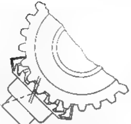


DEAD SPACE

Assume a condition of zero error. The order shaft is turned a fraction of a degree. Nothing happens. The shaft is then turned slowly until the load moves. The amount

occurrence

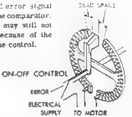
A comparator may have a small difference between order and response, and produce no error signal. This is due to dead space.



If the comparator is a geared differential, the "backlash" (or amount of play in the gearing) determines the dead space.

MECHANICAL DEAD SPACE

Suppose a small error signal is produced by the comparator. A motor signal may still not be produced, because of the dead space in the control.



ELECTRICAL DEAD SPACE

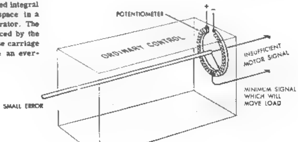
occurrence

Suppose that the control is producing a signal to the motor. When the control is variable, this signal will be small for small errors. This small signal might not be enough to overcome static friction, and start the load moving. The error necessary to cause a sufficiently large motor signal to overcome static friction is additional dead space in the system.

Total dead space in a system consists of the difference needed to produce an error in the comparator, plus the error necessary to produce a signal in the control, plus the signal required to start the motor and move the load.

INTEGRAL CONTROL

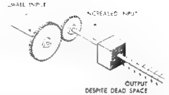
Dead space in the control, motor and load may be eliminated by proper construction of the servo system. A type of control, called integral control, will eliminate most dead space in a servo. The error is fed into an integrator. The carriage of the integrator is displaced by the error. Even slight displacement of the carriage will cause the integrator to produce an ever-increasing signal.



that the order shaft is turned before moving the load is called dead space. Dead space is the minimum error which will cause the system to activate the load.

reduction

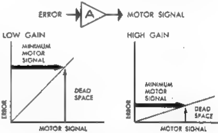
Mechanical dead space in the motor and control can be reduced by more exact construction of mechanical parts. However, some dead space is inevitable in any mechanism. The effect of dead space may be reduced by multiplying the input to the mechanism.



It is necessary in the above arrangement that there be little or no dead space in the gears as compared with dead space in the mechanism.

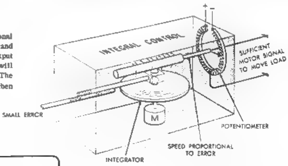
reduction

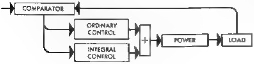
Just as dead space can be reduced mechanically by a high gear ratio, dead space may be reduced electrically by an amplifier with a high gain. Increased gain produces greater motor signals for smaller errors, thus decreasing the minimum error necessary to start the motor and move the load.



The speed of the integrator output is proportional to the error. Even when the error is small and the output speed is small, the fact that the output is continually moving means that eventually it will reach a value sufficient to move the load. The output of an ordinary control does not move when the error does not move.

In a servo system, integral control may be used together with ordinary control.





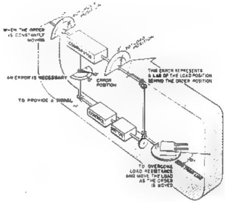
A system using integral control is extremely unstable, and is usually modified in use by high damping or by negative feedback.

LAG

Except for a brief discussion under stability we have always considered the order to be a constant value. We assumed that the order started at zero, was turned to a fixed position, and remained there while the load approached a position equal to the order position.

OCCURRENCE OF LAG

If the order to the servo is moving, the load must be moved. When dead space has been overcome, and the load is started in motion, there is still a certain amount of resistance in the load. Some motor torque is necessary to overcome this resistance. The only way to supply the torque is to have an error sufficient to turn the control to the proper value. The motor will then supply the required torque to the load. The error represents a difference in the positions of order and load. This difference in positions is called lag. Lag is similar to dead space because both are differences between the order position, and load position. Dead space is a difference needed in order to start the load moving, and lag is a difference needed to keep the load moving.



effect of control on lag

If the control used is an on-off control, the term lag is meaningless. Lag is caused by the constant small force exerted to overcome friction of the load while it is moving. An on-off servo does not exert such a small torque; it is either full power on, or full power off. Therefore, it will constantly catch up to, and fall behind, a moving input. It will not lag. Discussions of lag apply only to variable control servos.

constant speed lag

When the load is moving at a constant speed, the load resistance is composed of two types of friction:

1. Dry friction — Torque to overcome friction = constant = K_1
2. Wet friction — Torque to overcome friction is proportional to speed = K_2s

Each type of friction exerts a torque which opposes the motor torque. Total motor torque to overcome dry and wet friction is then:

Total motor torque = $K_1 + K_2s$

acceleration lag

If the load is accelerating, an additional torque will oppose the motor torque. This torque is caused by the inertia of the load. The torque required to overcome load inertia is proportional to acceleration:

Torque to overcome inertia = K_3a

Total motor torque to accelerate a load is then:

Total motor torque = $K_1 + K_2s + K_3a$

In order to produce this torque, a signal must be sent to the motor. To produce this signal, an error must be sent to the control.

To produce this error, there must be a difference between order and load position; the difference is lag.

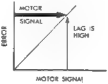
However, the order does not often remain at a constant position. For instance, the ordered position of a gun will constantly be changing as the target moves. When the order is moving, lag is the difference between order and load positions needed to keep the load moving.

REDUCTION OF LAG

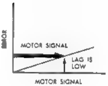
Increasing gain

Lag, like dead space, may be reduced by increasing gain. The motor signal is determined by the load resistance. With low gain, a large error, and therefore a large lag, will be required to produce this motor signal. With high gain, a small error, and therefore a small lag, will produce this motor signal.

CONTROL CHARACTERISTIC WITH LOW GAIN



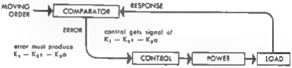
CONTROL CHARACTERISTIC WITH HIGH GAIN



positive feedback

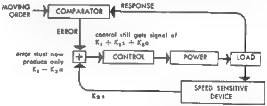
The reason for the existence of lag is that an error is necessary to produce a motor signal sufficient to move the load. But, if the proper motor signal could [redacted] produced without a large value of error, then lag could be reduced. Positive feedback tries to reduce lag in this way. Positive rate feedback measures the speed of the load, and adds this speed value to the error. Thus, the error itself need not be large in order to produce the proper motor signal. Since the error is reduced, the lag is correspondingly reduced.

SERVO WITHOUT POSITIVE FEEDBACK



Large Error and Large Lag

SERVO WITH POSITIVE RATE FEEDBACK



Small Error and Small Lag

Similarly, values K_1 and K_{3a} could be fed back and added to the error. Thus, the total value $K_1 + K_{2s} + K_{3a}$ could be fed to the control while the error remains at zero, thereby eliminating lag entirely.

SUMMARY

The purpose of a servo is to make the load position equal to the order position. Lag and dead space in a servo mean that the load position and order position are not equal. Therefore, they are undesirable features of a servo. Dead space may be reduced by increasing the gain, or by integral control. Lag may be reduced by increasing the gain, or by positive feedback.

A disadvantage of these measures [redacted] that they decrease the stability of a servo. Lag is reduced by positive feedback. Stability is improved by negative feedback. In general, a compromise must be reached between the amount of lag and the degree of stability in a servo system.

FREQUENCY RESPONSE

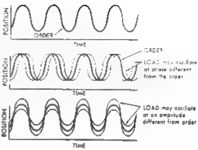
At first, we considered the order as being suddenly put at a fixed value. Later, we studied the case where the order slowly increased or decreased in value, where

MEANING OF FREQUENCY RESPONSE

The frequency response of a servo depends upon the range of frequencies over which the order may oscillate, and still produce similar oscillations in the load.

Assume that an oscillating order is put into a servo. The load may behave in several ways. Ideally, it would oscillate at the same frequency, amplitude, and phase as the order. Actually, the amplitude and phase of the load are different from those of the order. The frequency is usually the same as that of the order.

A servo may follow the order in amplitude, and differ in phase, it may follow the order in phase and differ in amplitude, or it may differ in both phase and amplitude.

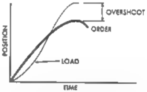


EFFECT OF GAIN AND DAMPING ON FREQUENCY RESPONSE

The higher the frequency of the order, the more difficult it is for a servo to accurately follow it. Damping and gain affect frequency response similarly to the way they affect lag. High gain, and low damping, will improve the frequency response.

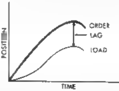
Frequency response is a good way of judging servo performance, because good frequency response involves a balance of damping and gain, so that maximum stability and least lag are attained. If a servo responds accurately to a wide range of frequencies, it has a correct balance between damping and gain.

HIGH GAIN-LOW DAMPING



Assume that a high frequency order is being put into the servo. If the servo has high gain, and low damping, in the rapidly increasing error at the beginning of the order motion will cause the load to leap to a response, and catch up to the order. However, when the order reverses direction, low damping and high gain will cause the load to overshoot.

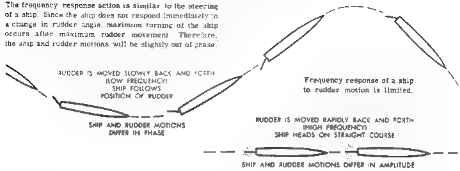
LOW GAIN-HIGH DAMPING



If the servo has low gain, and high damping, the load will move slowly while the order is changing rapidly, causing large lag. However, when the order changes direction, low gain will cause little overshoot.

it was constantly moving. Actually, the order to a servo may accelerate, start, stop, or oscillate about a fixed point. We will now consider actions of a servo while the order oscillates. When the order is constant, oscillations of the load are undesirable. When the order oscillates, the load must oscillate in a similar manner.

The frequency response action is similar to the steering of a ship. Since the ship does not respond immediately to a change in rudder angle, maximum turning of the ship occurs after maximum rudder movement. Therefore, the ship and rudder motions will be slightly out of phase.



Frequency response of a ship to rudder motion is limited.

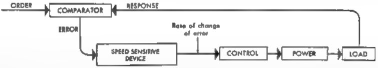
IMPROVEMENT OF FREQUENCY RESPONSE

by error rate control

A type of control which would have desirable frequency response is one with high gain when error is rapidly increasing, so as to immediately leap to response, and low or negative gain as the error is decreasing, so as to prevent overshoot.

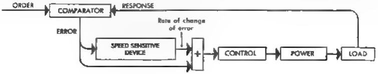
Error rate control is the type which will do this. The rate of change of the error, rather than the error itself, acts as the input to the control. For rapidly increasing errors, the control is turned to a high value. For rapidly decreasing errors, the control is turned to a negative value (braking action). For constant errors, the control is turned to zero.

Error rate control is achieved by measuring the error shaft speed by means of a speed sensitive device. The output of the speed sensitive device indicates the input to the control mechanism.



The disadvantage of error rate control is that when the error is not changing, no signal is sent to the motor. For oscillating orders, where the order is constantly changing, this handicap is not felt. But in servos, where the order might be expected to change slowly, the low rate of change of error might provide a motor signal insufficient to move the load. Thus, the order could increase slowly to a high value, without moving the load.

To overcome this disadvantage, the error signal is added to the error rate signal. With this arrangement, a very slowly changing (or low frequency) order has little effect on the error rate signal, and the system acts like a basic servo. When the order is changing rapidly, the error rate signal gives an added boost to the regular error signal, enabling the load to catch up to the rapidly changing order.



MATHEMATICAL ANALYSIS OF BASIC SERVO

DETERMINING GENERAL DIFFERENTIAL EQUATION

As we have seen on the previous page,

Total motor torque = torque to overcome dry friction
+ torque to overcome wet friction
+ torque to accelerate load
$= K_1 + K_2 s + K_3 a$

where K_1 = dry friction constant
K_2 = wet friction constant
K_3 = acceleration constant (inertia)

The input to the control is the error. The output torque of the motor is a function of the error. The nature of this function is dependent upon the characteristics of the control and the motor.

Total motor torque $= f(e) = K_1 + K_2 s + K_3 a$

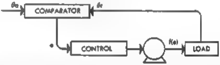
where e = error, and f(e) means function of error.

To obtain e, s and a in similar terms,

Order $= \theta o$
Response = load position $= \theta r$
Error $= e = \theta o - \theta r$
Load speed $= s = \dfrac{d\theta r}{dt} = \dot{\theta} r$
Load acceleration $= a = \dfrac{d^2\theta r}{dt^2} = \ddot{\theta} r$

the equation becomes:

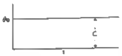
Motor torque $= f(\theta o - \theta r) = K_1 + K_2\dot{\theta} r + K_3\ddot{\theta} r$



STANDARD FORMS OF ORDERS

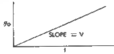
For purposes of system analysis, the standard ways of specifying the order are:

1. STEP ORDER



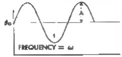
ORDER IS SET AT A VALUE AND REMAINS AT THAT VALUE
$\theta o = C$

2. RAMP ORDER



ORDER INCREASES AT A CONSTANT SPEED
$\theta o = Vt$

3. SINUSOIDAL ORDER



ORDER VARIES SINUSOIDALLY AT A CERTAIN FREQUENCY
$\theta o = A \sin \omega t$

We will study the step and ramp orders mathematically. The analysis of a sinusoidal order is complicated, and is discussed in a qualitative way in Frequency Response. Actually, the order may take any form. The above forms are merely standard for evaluating design of servos, and servo performance.

We have seen how it is possible to determine the relative stability and lag characteristics of servos without a mathematical analysis. The purpose of this discussion is to give the student the means to quantitatively evaluate these characteristics, as well as the ability to properly interpret the characteristics of a servo in mathematical terms.

When the control is variable, and the motor produces a torque proportional to the error,

Torque = f(error) = K_4(error)

where K_4 would be equal to system gain.

Then:

motor torque = $K_4(\theta o - \theta r) = K_1 + K_2\dot{\theta}r + K_3\ddot{\theta}r$ [Eq. 1]

The solution is an equation of the form:

$\theta r = f(\theta o)$ (GENERAL SOLUTION)

which is the response as a function of the order.

When the variation of the order with respect to time is known, we obtain the form:

$\theta r = f(t)$ (PARTICULAR SOLUTION)

The above is the general differential equation which mathematically describes operation of a basic servo.

The equation $\theta r = f(t)$ is used to analyze the behavior of the servo. In order to get this final equation, we must first specify the variation of the order with time.

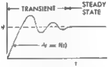
NATURE OF SOLUTION

There are two parts to the solution of the differential equation for each condition:

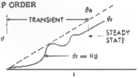
1. Steady state (after the servo has settled down).
2. Transient (before the servo has settled down).

The complete solution is the sum of the two parts.

STEP ORDER



RAMP ORDER



STATEMENT OF GENERAL STEADY-STATE SOLUTION

For a basic servo system the general solution for steady state is:

$$\theta r = \left(1 - \frac{K_2}{K_4} D + \frac{K_2^2 - K_4K_3}{K_4^2} D^2 + \frac{K_2^3}{K_4^3} D^3 + \ldots\right)(\theta o - K_1) \qquad \text{[Eq. 2]}$$

The equation is of the form $\theta r = f(\theta o)$. It consists of an infinite series. D is the derivative with respect to time.

$$D\theta = \dot{\theta}$$

D^2 is the second derivative with respect to time.

$$D^2\theta = \ddot{\theta}$$

The exponent of D is an indication of the number of times θ is to be differentiated.

K_1 is dry friction. It equals zero at all times when load speed equals zero. At other times it is constant. K_2, K_3, etc., are as defined above, and they are always constant.

MATHEMATICAL ANALYSIS OF BASIC SERVO

PARTICULAR STEADY-STATE SOLUTIONS

For a step order:

θo = constant = C

C is substituted for θo in [Eq. 2] (general) and the steady-state particular solution is:

$\theta r = \theta o$ — Only the first term of the general equation does not equal zero. $K_1 = 0$ at steady-state step order.

For a ramp order:

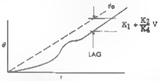
θo = constant x time = Vt

where V is the speed of θo (slope of ramp)

The value Vt is substituted for θo in [Eq. 2] (general), and the steady-state particular solution is:

$\theta r = Vt - K_1 - \frac{K_2}{K_4} V$ — Only the first two terms of the general equation are not equal to zero.

Since $\theta o = Vt$, θr will be less than θo by the amount: $K_1 + \frac{K_2}{K_4} V$



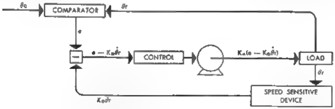
This is the amount of lag in the system. K_1 and K_2 are friction constants. Increasing them increases lag. V is the speed of the input. Increasing V increases lag. K_4 is the gain of the system. High gain means low lag.

Thus, mathematical analysis bears out conclusions reached previously. Lag is directly proportional to the damping, and is inversely proportional to the gain.

MATHEMATICAL ANALYSIS OF

DIFFERENTIAL EQUATION AND STEADY-STATE SOLUTION

The same type of analysis can be applied to a more complicated servomechanism; for instance, a servo with stabilizing negative feedback.



Since the speed-sensitive device is a differentiator,

output = constant x derivative of input
$= K_5\dot{\theta}r$

Motor torque $= K_4(e - K_5\dot{\theta}r) = K_1 + K_2\dot{\theta}r + K_3\ddot{\theta}r$

$K_4(\theta o - \theta r - K_5\dot{\theta}r) = K_1 + K_2\dot{\theta}r + K_3\ddot{\theta}r$

The general steady-state solution is:

$$\theta r = \left[1 - \left(\frac{K_2}{K_4} + K_5\right) D + (\ldots) D^2 + \ldots\right] \cdot \left[\theta o - K_1\right]$$

TRANSIENT SOLUTION

The above solutions apply only to the steady-state situation. The complete solution equals the sum of the above solution, and the transient solution. The transient solutions are complicated, and are not shown here. However, the result of analysis shows that if dry friction is negligible:

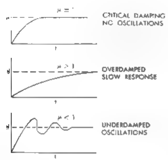
when

$$K_2 = 2\sqrt{K_3K_4}$$

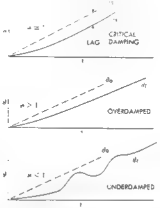
the system will arrive at a steady-state condition in the shortest possible time, without oscillations.

The ratio $\mu = \dfrac{K_2}{2\sqrt{K_3K_4}}$ is the damping ratio.

STEP ORDER



RAMP ORDER



Most servos are designed so that their damping ratio is unity, or close to unity. Sometimes, slight oscillations are permitted.

SERVO WITH RATE FEEDBACK

PARTICULAR STEADY-STATE SOLUTIONS

For a step order, θo = constant = C and the steady-state solution is:

$\theta r = \theta o$, as before.

For a ramp order $\theta o = Vt$ and the steady-state solution is:

$$\theta r = Vt - K_1 - \left(\frac{K_2}{K_4} + K_5\right) V$$

The lag for a servo with stabilizing (negative) feedback is:

$$K_1 + \frac{K_2}{K_4} V + K_5 V$$

This lag is greater than the lag of the basic servo by the amount K_5V.

TRANSIENT SOLUTION

A transient analysis shows that the damping ratio is:

$$\mu = \frac{K_2 + K_5V}{2\sqrt{K_3K_4}}$$

The higher ratio means that the servo is more stable with negative feedback than without it. This confirms our previous qualitative analysis.

SUMMARY

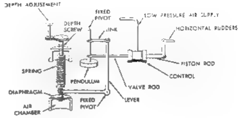
Similar analyses can be made of other types of servos. Positive feedback does exactly the opposite of negative feedback. It decreases the lag by the amount K_5V, but also decreases the damping ratio, causing instability. It will be found upon analysis that integral control will also reduce lag, and reduce the damping ratio. Dead space, because of its discontinuous nature, is difficult to analyze mathematically.

APPLICATION

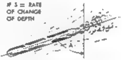
TORPEDO DEPTH CONTROL

The torpedo depth control mechanism is a servo which may be analyzed in relation to principles studied in this chapter. Consider the action of the depth control mechanism.

A spring is set in tension by turning the depth adjustment (order). The water pressure acts against this spring by pushing on a diaphragm. Pressure is proportional to the depth of the torpedo (response). Assume that the torpedo is at a lower depth than the ordered value and inclined down. The difference in pressures (error) is transmitted through linkages to the pneumatic control which controls the power positioning the horizontal rudders. The horizontal rudders move the torpedo (load) upward in the water.

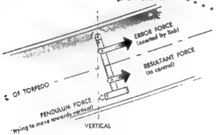


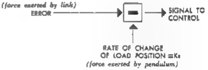
The pendulum measures the angle of the torpedo from the vertical. This angle is proportional to the rate of change of depth. The pendulum force is subtracted from the error force by the linkage.



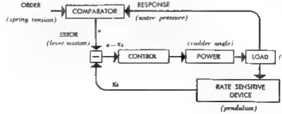
ANGLE A PROPORTIONAL TO RATE OF CHANGE OF DEPTH = Ks

the function of the pendulum . . . IS TO PERFORM THE FOLLOWING SUBTRACTION

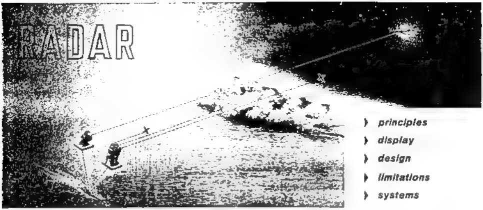




The entire system is a servo with negative rate feedback.



RADAR



- principles
- display
- design
- limitations
- systems

THE PROBLEM OF VISIBILITY

poor visibility decreases efficiency

A man is driving his car along a winding road and into a fog. The driver's vision is restricted. He must reduce his speed, and be alert to avoid obstacles which may lie in his path. The reduced visibility has forced the driver to cut down his speed. Therefore, his efficiency in reaching his destination on time is reduced.

Poor visibility will also decrease naval operational efficiency. Visual navigation becomes difficult or impossible; speed must be reduced to prevent collisions. Fire control dependent on optical sighting is impossible in darkness, fog and smoke screens and impaired by glare, haze and clouds. Thus, the efficiency of a ship which relies solely on optical navigation or fire control is directly dependent on conditions of visibility.

system needed to operate in all visibility conditions

The reduction of the driver's efficiency may result only in some minor inconvenience. Decrease of naval efficiency in time of war could result in extensive loss of life and equipment. Thus, a means had to be devised to obtain full operational efficiency regardless of visibility conditions.

RADAR SOLVES THIS PROBLEM

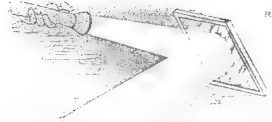
radar system developed

Shortly after World War II began, a detection system, known as RADAR (RAdio Detection And Ranging), was developed. It was used in addition to the optical means of sighting and navigating. Radar enables a ship to detect obstacles, other ships and objects through any visibility condition — fog, glare, darkness and smoke screens. Thus, the human element and optical system can be replaced by an accurate electronic system. Radar is the primary detection means on modern ships.

Since radar replaces optical sighting, it must function to provide the same information as an optical system. Radar searches the area as a lookout, locating any objects in its path. It gives accurate range, bearing and elevation information of objects far beyond the sight of a lookout. While the radar operator can perform his duties below deck, lookouts must be stationed on deck, exposed to the elements of weather which cause a lowering of operating efficiency.

SCOPE OF CHAPTER

Shortcomings of optical sighting have been noted above, and the role of radar, which overcomes these shortcomings, was introduced. In the following pages, it will be shown how radar overcomes these shortcomings. The basic principles and design aspects of radar will be discussed. Limitations due to operational and design factors, and the method of displaying radar information, will be covered. Finally, to give the student a complete picture of radar, integrated system operation will be discussed.



THE ECHO PRINCIPLE . .

Radar searches by sending out energy in a beam. When this energy hits an object in its path, some of the energy is reflected to the radar. The detection of objects by reflecting energy off their surfaces is known as the echo principle.

To illustrate the echo principle operation in radar, we will consider a familiar example of the same principle, using light. Then, the analogous operation of the echo principle in radar will be shown.

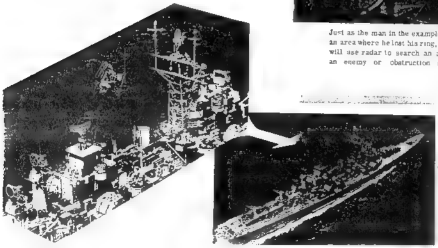
A valuable ring is lost . . . .

LIGHT

What lies ahead . . enemy? . . obstruction? . . . .

RADAR

Just as the man in the example searched an area where he lost his ring, the captain will use radar to search an area where an enemy or obstruction might be.



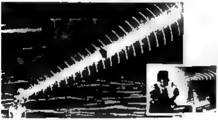
. . . .

. . detection of objects

. . . Surrounding area SEARCHED with flashlight

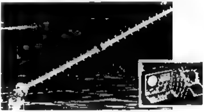
. . . REFLECTED LIGHT hits man's eyes, and RING IS LOCATED

. . . . Radar SEARCHES with electrical energy beam . . . .



Radar searches with a beam of electrical energy instead of with a beam of light. This energy is produced by a transmitter, and is sent out from an antenna. The transmitter and antenna are similar in principle to those used by radio broadcasting stations.

. REFLECTED ENERGY bounces back to receiver and OBJECT IS LOCATED



When the beam of electrical energy hits an object in its path, the energy is reflected. Some of this reflected energy travels back to the antenna, and is picked up by a receiver. The receiver is similar in principle to a radio receiver.

Note

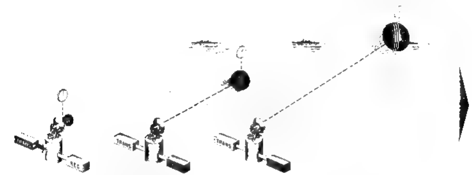
Although the physical appearance and technical details of radar equipment vary greatly from set to set, all radar sets use the echo principle.

summary

From this discussion, we have seen that radar searches with a beam of energy, and detects objects in the beam by the echo principle. On the following pages, the manner in which radar uses the echo principle to determine the range and direction of an object will be discussed.

THE TIMING PRINCIPLE . . . .

The energy transmitted in radar is of a known speed "[328 yards/microseconds (yd/usec.)]". When this energy strikes a target, an echo is produced which travels back to the receiver. The time of the energy travel to the target and back is in the order of microseconds, and can be precisely timed by electronic means. Then, knowing the speed and time, the distance of the energy travel is calculated. The range to the target is one-half this round trip distance.



Radar transmitter is turned on and off . . .

. . . producing a burst of electrical energy.

When energy strikes target, ...

REQUIREMENTS FOR TIMING ENERGY TRAVEL

There are two requirements for the timer shown in the above illustrations:

time sweep

To determine the time between transmission and reception, an indicator which moves at a constant speed over a known time interval is used. The indicator movement over the known time interval is called the time sweep. The time between any two points on the time sweep can be determined.

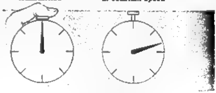
marking transmitted and received pulses

By marking the time of transmission and the time of reception on the time sweep, the energy transit time is determined.

These timing requirements are seen in the operation of a stopwatch . . . .

energy is transmitted

energy moves at constant speed

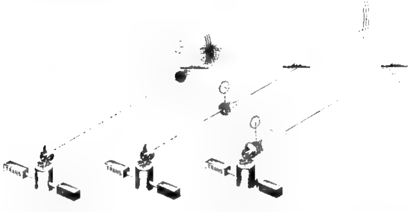


timer is started

indicator moves at constant speed

marking transmitted pulse

time sweep



. . . . . . energy is reflected.

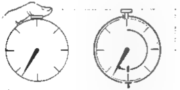
Some energy returns toward radar.

Returning echo is received by radar.

. . . . performing one revolution

in a known interval of time

echo is received



timer is stopped

By comparing length t with length T (known interval of time), the energy transit time is determined

marking received pulse

summary

Intervals timed in radar are in the order of microseconds. The stopwatch was shown to demonstrate the timing requirements, and could not be used to time such short intervals.

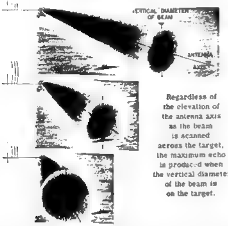
Electronic means, used for timing and displaying range information, fulfill the same requirements. Timing and range display, by means of the cathode ray tube, are discussed later in the chapter.

THE SCANNING PRINCIPLE . .

Radar energy is directed into a beam by the antenna. The radar beam varies in intensity, being stronger along the antenna axis and decreasing in intensity as the angle from the antenna axis increases.

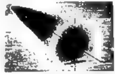
scanning in one plane . . .

Target direction, in one plane, is determined by scanning the beam in that plane.



Regardless of the elevation of the antenna axis as the beam is scanned across the target, the maximum echo is produced when the vertical diameter of the beam is on the target.

The direction producing the maximum echo is noted as the beam is scanned across target.



To get on target, the beam is then moved to the direction producing the maximum echo.

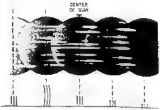
To determine direction in a horizontal plane, the vertical diameter of the beam must be scanned across the target.

To determine direction in a vertical plane, the horizontal diameter of the beam must be scanned across the target.

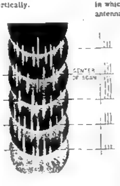
scanning in two planes . . . .

To get the radar on an aerial target, both the horizontal and vertical deviations of the target from the antenna axis must be determined.

To determine the horizontal deviation, the beam is scanned horizontally.



To determine the vertical deviation, the beam is scanned vertically.



The resultant of the horizontal and vertical deviations shows the direction in which to move the antenna axis to get on target.

When the target is moving horizontally and vertically, both the horizontal and vertical deviations constantly change. To obtain accurate resultant deviation, both the vertical and the horizontal deviations must be determined at the same time.

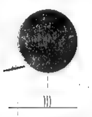
. determination of direction

The magnitude of the echo depends on the position of the target in the beam. The maximum echo is produced when the target is in the strongest part of the beam; that is, when the target is on the antenna axis. Thus, in order to determine the target direction, the beam is moved until the echo received is maximum.

The movement of the radar beam to determine the maximum echo is known as scanning. The manner in which the radar beam should be scanned to determine the target direction will now be discussed.

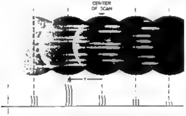
.. determination of bearing

Suppose the target is moving, and moves off the beam diameter.



The echo magnitude decreases, indicating that the target is no longer on the beam diameter. But the direction in which the target has moved is not indicated. In order to determine the new direction of the target, the beam diameter must be again scanned across the target.

To facilitate following a moving target, the beam diameter is continually scanned across the target.



Scanning in one plane precisely locates targets in only one plane. It is used in surface fire control to determine bearing of ships, targets of known elevation.

By timing when the maximum echo occurs, the target deviation from the center of the scan is determined.

.. determination of bearing and elevation

The resultant deviation of the target can be found directly by employing a different kind of scan; that is, scan by rotating the beam in a circle.

When a target is in the scanned area, the beam diameter crosses the target at a particular angular displacement, causing maximum echo. By timing when the maximum echo takes place, the angular direction of the target from the start of scan is determined. Displacement of the target along the angular direction depends upon the ratio between the maximum echo and the minimum echo in the scan.

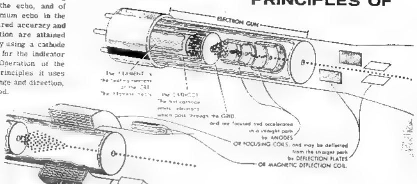
The method of scan shown is called conical scan because the beam traces a cone.

SUMMARY

Accurate timing is required in determining direction by scanning. The cathode ray tube is used to display the target position in the scanned area. Direction display is discussed later in the chapter.

PRINCIPLES OF

Radar requires a means of timing the transit of the echo, and of indicating maximum echo in the scan. The required accuracy and speed of operation are attained electronically by using a cathode ray tube (CRT) for the indicator of the radar. Operation of the CRT, and the principles it uses in displaying range and direction, are now discussed.



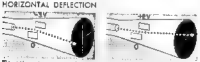
DEFLECTION OF LIGHT SPOT

Light spot deflection may be accomplished by two different means—deflection plates, used in an electrostatic CRT, a magnetic deflection coil, used in an electromagnetic CRT.

deflection plates

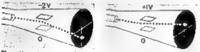
An electron is a negative charge. It is attracted to a positive-charged body, and repelled by a negative-charged body. To attract or repel the electrons from a straight path, it is necessary only to put a voltage charge on one of the deflection plates. The greater the voltage, the greater the attraction or repulsion.

HORIZONTAL DEFLECTION



To attract or repel the light spot horizontally, a voltage is applied to the horizontal deflection plates.

VERTICAL DEFLECTION



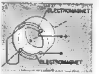
To attract or repel the light spot vertically, a voltage is applied to the vertical deflection plates.

HORIZONTAL AND VERTICAL DEFLECTION

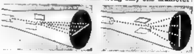
To attract or repel the light spot horizontally and vertically, voltages are applied to both sets of deflection plates.

magnetic deflection coil

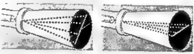
The electron stream may be deflected from a straight path by energizing the magnetic deflection coil. The electron stream is deflected by the field between two electromagnets. As with the deflection plates, the greater the intensity of the signal, the greater the attraction or repulsion of the light spot.



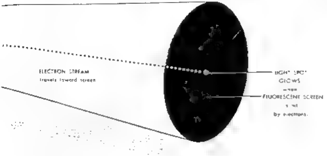
A set of deflection plates, mounted internally, can deflect the electron stream along only one diameter.



Because the magnetic deflection coil is mounted externally, it can be oriented to deflect the electrons along any diameter.



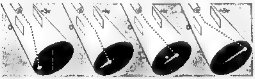
THE CATHODE RAY TUBE



In the display of radar information, the electron stream and light spot can be deflected from the center, swept across the screen, and also can be varied in brightness (intensity modulation). These are used individually, or in combination, to display information. These three ways of affecting the screen display are discussed below. Their uses in radar indicators are shown on the following pages.

SWEEP OF LIGHT SPOT

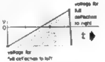
As the voltage on the deflection plates increases, the electron stream and light spot are deflected across the screen. Because of the screen persistency, a line of light glows along the path of the light spot.



sweep voltage

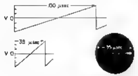
When the voltage increases uniformly with time, the light spot moves at a constant speed across the screen. Then, the voltage returns to its original value, and the light trace returns to its starting position. This return is made as short as possible, and is blacked out on the screen.

Because it causes the light spot to sweep across the screen, this voltage is known as a sweep voltage. Because of its shape on the graph, it is called a sawtooth voltage.



sweep time

The speed of the light spot can be increased by making the sweep voltage change in a shorter period of time (sweep time).

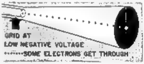


sweep time depends on slope of sweep voltage

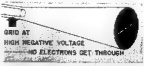
A voltage applied to the magnetic deflection coil similarly causes the light spot to sweep at a constant speed across the screen.

INTENSITY MODULATION OF LIGHT SPOT

The brightness of the light spot depends on the number of electrons which hit the screen. The cathode is always emitting about the same number of electrons. The value of voltage applied to the grid controls the number of electrons from the electron gun.



When the grid is made slightly negative, the electrons are repelled back toward the cathode. But some electrons will have sufficient energy to get by the grid.



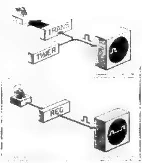
Thus, by varying the voltage on the grid, the brightness of the light spot can be varied.

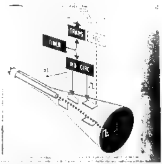
DISPLAY OF RANGE

Range is displayed on a time sweep by VERTICAL DEFLECTION

In the display of range by vertical deflection, time of transmission is indicated on the time sweep by applying a voltage pulse to the vertical deflection plates at transmission.

Time of reception is indicated on the time sweep by first converting the echo into a voltage pulse, and then applying it to the vertical deflection plates.





HOW THE CRT USES VERTICAL DEFLECTION AND TIME SWEEP TO DISPLAY RANGE.

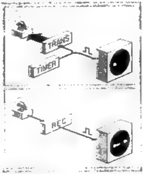
Timer causes vertical deflection, and starts sweep as it triggers transmitter pulse.

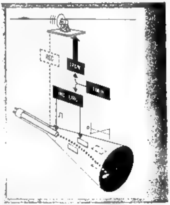
Range is displayed on a time sweep by INTENSITY MODULATION

In the display of range by intensity modulation, the grid is initially made negative. The time sweep is then a faint spot sweeping across the screen.

At the time of transmission, a voltage pulse is applied to the grid, making the grid less negative. More electrons are emitted from the electron gun, and a bright spot is produced on the screen, marking the time of transmission.

The received echo is converted into a voltage pulse which is applied to the grid, making the grid less negative. More electrons are emitted from the electron gun, and a bright spot is produced on the screen, marking the time of reception.

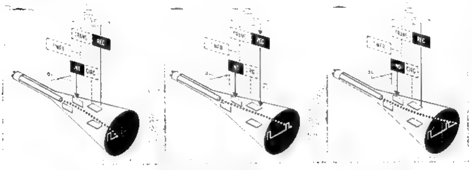




HOW THE CRT USES INTENSITY MODULATION AND TIME SWEEP TO DISPLAY RANGE.

Timer causes bright spot, and starts sweep as it triggers transmitter pulse.

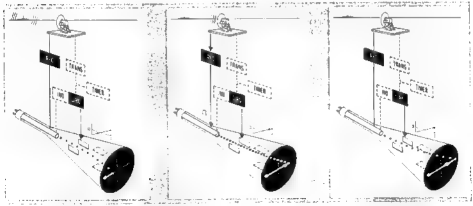
The requirements for timing energy transit have been previously discussed. In review, the requirements are a time sweep and a means of marking the times of transmission and reception of energy. The sweep of the light spot on the CRT fulfills the requirements for a time sweep. Two means used to mark transmission and reception on the time sweep and, thereby, determine range, will now be discussed.



Spot sweeps across screen at constant speed proportional to speed of radar energy.

Received echo pulse causes vertical deflection on screen.

Sweep voltage continues spot to end of sweep.



Spot sweeps across screen at constant speed proportional to speed of radar energy.

Received echo pulse causes bright spot on screen.

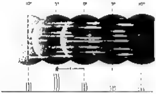
Sweep voltage continues spot to end of sweep.

DISPLAY OF DIRECTION

An intensity modulated, electrostatic CRT is used in the display of direction. The grid is initially made negative. When an echo is received, the grid is made less negative, allowing more electrons to come from the electron gun, and producing a bright spot on the screen. The position of the spot with respect to the center of the screen is made to represent the position of the target with respect to the center of the scanned area.

display of bearing

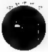
The principle of timing to the maximum echo to determine target deviation from the center of scan was previously discussed.



HOW THIS BEARING DISPLAY IS ACCOMPLISHED

A voltage (EB), proportional to the angle between the center of the scan and the axis of the antenna, is applied to the deflection plates. The light spot deflection from the center of the screen represents the antenna deviation from the center of the scan.

This information is displayed on the screen as shown below:



display of bearing and elevation

The principle of timing to the maximum echo to determine target direction and deviation from the center of scan was previously discussed.

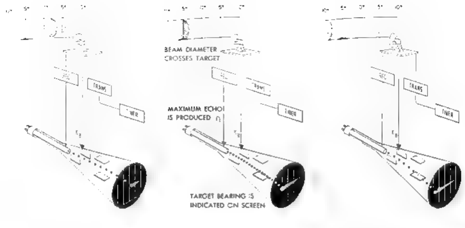
As the beam is scanned, the echo magnitude varies sinusoidally.

HOW THIS BEARING AND ELEVATION DISPLAY IS ACCOMPLISHED

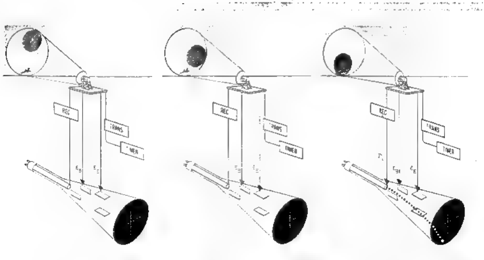
The variation of the echo is compared to a voltage proportional to the angle in elevation between the center of scan and the antenna axis. This voltage is also sinusoidal. The displacement in elevation is determined by the difference in phase of the two voltages, and the magnitude of the echo voltage variation. This elevation displacement is converted into a d.c. voltage (Eg) which is applied to the vertical deflection plates.

Similarly, by comparing the echo voltage to a voltage proportional to the angle in bearing between the center of scan and the antenna axis, the bearing displacement as a d.c. voltage is determined. This d.c. voltage (EB) is applied to the horizontal deflection plates.

This information is displayed on the screen as shown below:

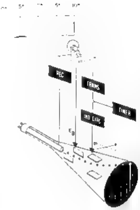


note E_B is called bearing sweep voltage, because it sweeps the light spot in bearing as the antenna sweeps in bearing. E_B can be produced by using a potentiometer which is rotated as the antenna is rotated.



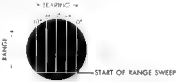
note The brightest part of the spot, the center, is caused by the maximum echo. The weaker sides of the spot are caused by fairly strong echoes immediately preceeding and following the maximum echo.

COMBINED RANGE AND BEARING DISPLAY



B-SCOPE

The B-Scope display is produced in the same way as the bearing display, with the addition of a range sweep applied to the vertical deflection plates



Instead of having a faint spot of light at each bearing of the antenna as it scans (as in bearing display), the faint light spot of the B-Scope sweeps vertically in range. The range sweep spot moves rapidly with the respect to the antenna scanning rate. Therefore, the screen has the appearance of a vertical trace of light being swept in bearing as the antenna is scanned.

P-SCOPE

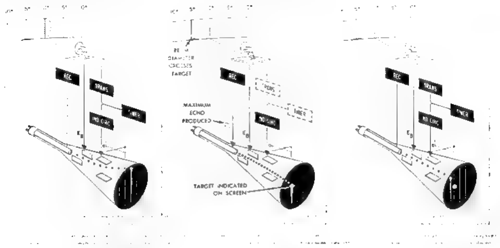
The P-Scope presents bearing and range in a display that may be regarded as the equivalent of an aerial chart of the surrounding area.

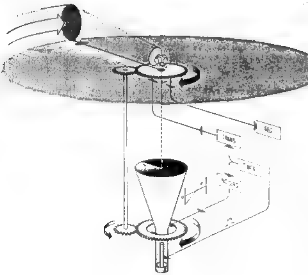
The range sweep moves rapidly with respect to the antenna rotation rate. Therefore, the screen has the appearance of a radial trace of light being continuously rotated in bearing as the antenna is continuously rotated.

The P-Scope display utilizes an electromagnetic CRT. A range sweep is applied to the magnetic deflection coil. The light spot is swept radially to indicate range.
The external magnetic deflection coil is rotated as the antenna is rotated. The range sweep line is made to point in the same direction the antenna is pointing. Thus, the light spot sweeps radially (range) as it is rotated to correspond to the antenna rotation (bearing).

For a surface target, bearing and range provide the required position information. It is advantageous to display both bearing and range on the same screen.

This is accomplished in the B-Scope, which displays range and a small angle in bearing, and in the P-Scope which displays range and the complete 360° in bearing.





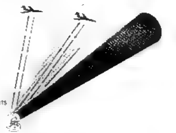
SUMMARY

The various screen displays shown are merely a few examples of the many types in actual use. Since radar indicators use the CRT principles discussed, the characteristics and operation of any particular screen display can usually be determined.

DESIGN

The capabilities of radar are determined by its electronic design. The design features of pulse repetition frequency, power and pulse length are related to the range of radar.

PULSE REPETITION FREQUENCY



THE NUMBER OF PULSES TRANSMITTED PER SECOND, IS CALLED THE PULSE REPETITION FREQUENCY (PRF)

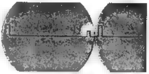
REQUIRED RADAR RANGE DETERMINES PRF

Suppose the PRF were 1000 pulses/sec.

Then, any echoes must be received within 1000 µsec. If one should arrive later, say in 1200 µsec., ...

it would be mistaken for a short range echo of the second transmitted pulse.

An echo at 1200 µsec. would be produced by a target about 100 miles away. If this range is required of the radar, the PRF must be lowered to allow the echo from that distance to return before the next transmitted pulse.



Thus, the maximum required range determines the highest PRF that can be used.

example A 5-inch gun with a range of 40,000 yards would require a fire control radar with a maximum range of about 60,000 yards. Then, because echoes beyond 60,000 yards are of no interest to the fire control radar of the 5-inch gun, its PRF can be designed to include only up to that range.

PRF DETERMINES

screen clarity . . . . screen persistency

With a low PRF, the fuzziness or grass along the trace of the screen is large. It may be large enough to hide a small target echo.

LOW PRF

But with a high PRF, the grass is smaller, and a small echo will not be as easily hidden in the grass.

HIGH PRF

In order for the target to be continuously displayed, its echo pulse must remain on the screen until the next echo pulse appears; then, it must disappear. If it stays too long on the screen, the image will be obscured. If it disappears too soon, the image will be faint and undiscernable. This quality of the screen to hold an image after it has been traced on it is called screen persistency. Screen persistency must be chosen to correspond with the PRF.

The range sweep design determines the accuracy possible on the display of range. On the following pages, these important design features of radar will be discussed.

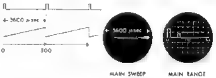
DESIGN OF RANGE DISPLAY

RANGE SWEEP

Previously, it was shown that the speed of the spot on the screen can be varied by varying the time of the sweep voltage. The use of this will now be discussed.

main sweep

Suppose we have a radar with a range of 300 miles. This means we need a 3600-μsec. interval between transmitted pulses. The spot is swept across the screen in 3600-μsec. This sweep is known as the main sweep, because all the targets in the required range are displayed on the screen.



MAIN SWEEP MAIN RANGE

expanded sweep

In order to read accurately at short ranges, the range display can be decreased to read from 0 to 100 miles. This is done by decreasing the time of the sweep to 1200 μsec. Because the short range portion is expanded to cover the entire screen, this sweep is known as the expanded sweep. The interval between pulses is still 3600 μsec. Echoes arriving between 1200 and 3600 μsec. will not be displayed, as there is no sweep at that time.

EXPANDED SWEEP EXPANDED RANGE

precision sweep

A further modification is to allow a decreased range sweep to sweep over any part of the total 3600 μsec. interval. If we decrease the sweep to 300 μsec., the range displayed will be 25 miles. This display can be made to cover any 25-mile interval from 0 to 300 miles by delaying the start of the sweep. The sweep can be started any time during the 3600-μsec. interval between transmitted pulses. This sweep is known as the precision sweep, because the range of targets in the sweep can be precisely determined.

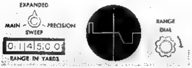
PRECISION SWEEP PRECISION RANGE

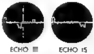
RANGE MARKER

On a radar set that has more than one range display, the scope cannot be directly graduated in units of range. For example, for three different sweeps, we would need three different scales.

A range marker is used to determine the range of a target. On an A-Scope, the range marker is a range step which is a sharp drop in the trace line. The range step is moved along the trace line by a range dial. When a target echo is in the front end of the range step, target range is indicated on a counter.

On a B-Scope, a range line, using the same principle as the range step, is moved vertically to indicate range.





ECHO IS NOT GATED ECHO IS GATED

This range marker is important for another reason. The range information must be computed before the radar will track a target. Range is computed by moving the range marker to the target echo. This is known as "gating the echo" in range.

POWER AND

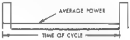
peak power and average power

Peak power is the amount of power the transmitter produces.
The greater the peak power, the greater the range of the radar.

Radar energy is the energy produced when
peak power radiates for time of transmission (pulse length).

RADAR ENERGY = (PEAK POWER) x (PULSE LENGTH)

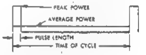
Average power is the power level, transmitting for the entire cycle, which would produce the same amount of energy as the peak power transmitting for the pulse length. The greater the average power, the greater the size of the radar transmitter required to produce it.



$$\text{AVERAGE POWER} = \frac{\text{(PEAK POWER) x (PULSE LENGTH)}}{\text{TIME OF CYCLE}}$$

duty cycle

Radar equipment is designed for a large peak power with as small an average power as possible. The ratio of average power to peak power is known as the duty cycle. Thus, we see that the radar is designed for the lowest possible duty cycle.



$$\text{DUTY CYCLE} = \frac{\text{AVERAGE POWER}}{\text{PEAK POWER}} = \frac{\text{PULSE LENGTH}}{\text{TIME OF CYCLE}}$$

The duty cycle can be lowered by making the time of cycle large as compared to the pulse length. By increasing the time of the cycle, the PRF will be changed. We have seen previously that the PRF used is determined largely by other considerations. However, the pulse length can be decreased to give a low duty cycle. Pulse length in present radar sets [illegible] designed to be approximately 0.3 μsec. to 5 μsec., depending on the use of the radar.

The duty cycle of a radar with a pulse length of 0.3 μsec., and a PRF of 2000 pulses/sec., is:

$$\text{Time of Cycle} = \frac{1}{\text{PRF}} = \frac{1}{2000} = 500\ \mu\text{sec.}$$

$$\text{Duty Cycle} = \frac{\text{Pulse Length}}{\text{Time of Cycle}} = \frac{0.3\ \mu\text{sec.}}{500\ \mu\text{sec.}} = 0.0006$$

Then, if a peak power of 150,000 watts is needed to attain a certain range, the average power is:

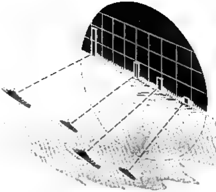
Average Power = (Duty Cycle) x (Peak Power) = (0.0006) x (150,000 watts) = 90 watts.

Thus, for a peak power output of 150,000 watts, the transmitter average power is only 90 watts.

PULSE LENGTH

peak power and maximum range

It was shown previously that maximum receivable range depends on PRF. But it does so only in a timing sense. Maximum range also depends on transmitter peak power output. The greater the range of the target, the lower will be its echo power. Past a certain range, depending on the power of the set, the echoes will be hidden in the trace fuzziness. To increase the range, the transmitter peak power must be increased.



note

Maximum range is also dependent on receiver sensitivity; that is, the degree an echo is amplified after it is received. The amount of this amplification is limited by electronic design capabilities.

average power and maximum range

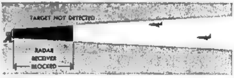
By increasing the average power transmitted, the returning echoes have a greater average signal strength. This aids the receiver in the detection of weak echoes, and thus increases the maximum range of the radar. A greater average power is achieved on long range radars by using long pulse lengths.

pulse length and minimum range

A receiver is designed to receive pulses having amplitude in the microwatt range. When the transmitter is sending out a pulse, the receiver must be turned off; otherwise the large transmitter power would overload and saturate the receiver. Saturation would prevent the reception of echoes for what could be a considerable length of time.

The receiver is blocked for an interval about three times the length of transmission. If the pulse is 1 μsec. long, the receiver is blocked for about 3 μsec.

This means that, after transmission of a pulse, any echo returning to the receiver before 3 μsec. have elapsed will not be received and displayed. Thus targets up to 500 yards in range will not be detected.



If the radar is a short range fire control radar, this might be a sizeable area of the scope. The pulse length would have to be shortened to receive echoes from short range targets. However, on radar with a range of hundreds of miles, blocking of the receiver for a short range is not critical. Long range radars use pulse lengths up to 5 μsec.

note

Short pulse lengths are used on short range fire control radars because they provide better range discrimination; that is, they are able to distinguish between closely spaced targets. This will be discussed in detail in DISCRIMINATION.

LIMITATIONS

Radar is limited in its performance by factors external to the equipment, as well as the design features of the equipment. The limitations introduced by such design features as PRF, power, and

OPERATIONAL . .

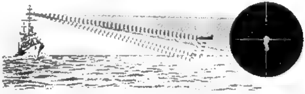
curvature of the earth

The maximum range of a surface radar, with no size restrictions limiting the power output, is limited by the curvature of the earth.

false echo

When a radar pulse hits an object it reflects in all directions. Part of it travels directly back to the radar. Part of it may travel back indirectly (such as reflecting off the surface of the water). Such an echo will arrive later than the true echo, because it has a longer distance to travel.

In addition [illegible] false echoes on the A-Scope, when tracking low flying aircraft, inaccurate information on elevation is also presented.



natural interference

Large objects, such as land masses, obscure nearby targets. The ship echo and the building echo are both masked by the echo from the land. The reason for this is explained in DISCRIMINATION.

Thunderstorms cause indications on the scope. The indications appear as fluctuating ragged pips, sometimes varying over a considerable range.

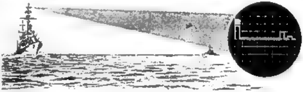
pulse length, were explained. Now, we will give consideration to some operational limitations caused by external factors, and also to the additional design limitation of discrimination.

due to external factors

The range of air search radar is not affected by the earth's curvature. The range is restricted by maximum receiver sensitivity and increased equipment size with increased peak power.

two echoes

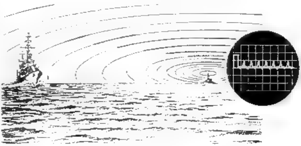
When tracking a target, a second echo appearing on the scope may cause momentary confusion. This can be avoided by continuously viewing the tracking on the scope. If the correct echo can not be readily identified, it can usually be determined by evaluating both echoes as to their size, speed, etc.



man-made interference

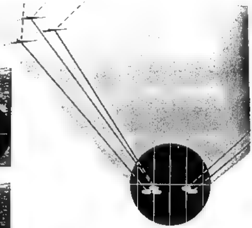
Other radars operating on the same frequency and PRF sometimes cause interference on the scope. This may be accidental interference between friendly radars, or may be deliberate interference caused by the enemy.

Deliberate interference, called jamming, is an attempt by the enemy to lessen the usefulness of our radar. An experienced radarman can recognize jamming, and still effectively operate with the jamming, or he may be able to reduce or eliminate it.

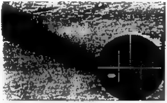


DISCRIMINATION • •

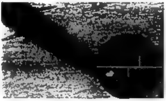
The ability of a radar to discriminate between objects close in bearing is called bearing discrimination.



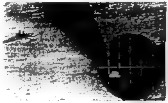
The first pip is caused as the beam diameter sweeps across the first ship.



The radar is receiving strong echoes from both the first and second ships at the same time, and the pips overlap.



The strong part of the beam is hitting both the second and third ships at the same time, causing their echo pips to overlap.

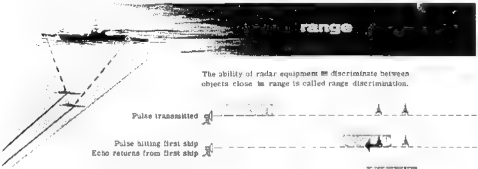


BEARING DISCRIMINATION DEPENDS ON FOCUS OF BEAM

As the beam sweeps from the first ship to the third, strong echoes are continually being received by the radar. Thus, one long pip mass will appear on the scope. The difference in range between the ships keeps the pip mass from appearing as a single long pip.

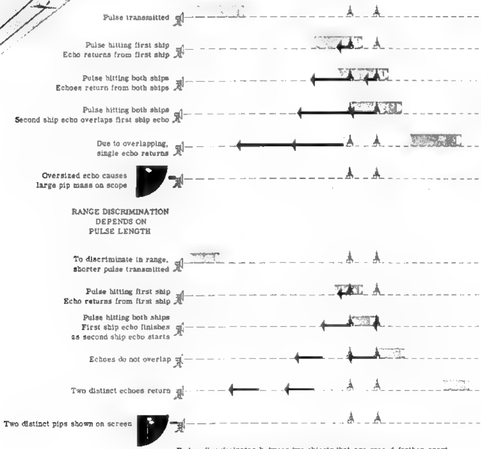
To discriminate in bearing, a narrower focused beam can be used. The beam fits between the ships, giving a time in which no strong echoes are received, thereby providing a space in bearing between the pips from the first and second ships and the second and third ships.

Discrimination in radar is the ability to distinguish between closely spaced objects. Echoes from objects too close in bearing or range overlap, causing a pip mass to be displayed instead of a distinct pip for each echo. This hampers target identification and evaluation. The factors affecting discrimination will now be discussed.



range

The ability of radar equipment to discriminate between objects close in range is called range discrimination.

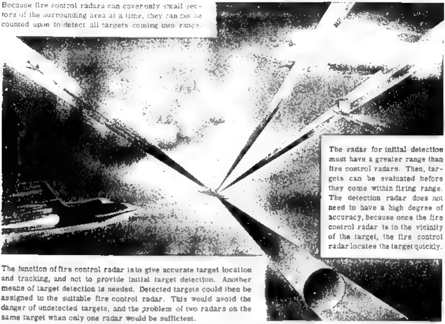


Radar discriminates between two objects that are spaced farther apart than one half the pulse length. For example, a pulse length of 100 yards (0.3μsec.) will discriminate between objects more than 50 yards apart.

SYSTEM OPERATION

TARGET DETECTION

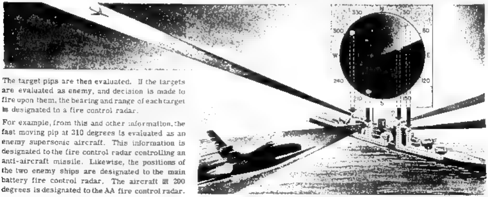
Because fire control radars can cover only small sectors of the surrounding area at a time, they can not be counted upon to detect all targets coming into range.



The radar for initial detection must have a greater range than fire control radars. Then, targets can be evaluated before they come within firing range. The detection radar does not need to have a high degree of accuracy, because once the fire control radar is in the vicinity of the target, the fire control radar locates the target quickly.

The function of fire control radar is to give accurate target location and tracking, and not to provide initial target detection. Another means of target detection is needed. Detected targets could then be assigned to the suitable fire control radar. This would avoid the danger of undetected targets, and the problem of two radars on the same target when only one radar would be sufficient.

TARGET EVALUATION



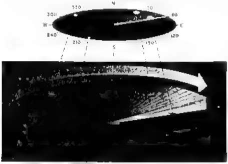
The target pips are then evaluated. If the targets are evaluated as enemy, and decision is made to fire upon them, the bearing and range of each target is designated to a fire control radar.

For example, from this and other information, the fast moving pip at 310 degrees is evaluated as an enemy supersonic aircraft. This information is designated to the fire control radar controlling an anti-aircraft missile. Likewise, the positions of the two enemy ships are designated to the main battery fire control radar. The aircraft at 200 degrees is designated to the AA fire control radar.

The radar chapter, thus far, has been concerned with radar in general, and fire control radar in particular. However, before a fire control radar can function in acquiring and tracking a target, the functions of initial detection, evaluation and designation must be accomplished. The operation of a radar system from initial target detection to target tracking will now be discussed.

search radar

For initial target detection, long-range search radar is used. It differs in many features from the fire control radar. The beam is broadly focused in width and height to enable it to search a more extensive area. It is slowly and continually scanned in a full 360 degrees around the ship. A high persistency screen is used on the P-scope because of the relatively slow rate of rotation. Other design features are long pulse length and high receiver sensitivity for best reception of weak echoes, and high peak power and low PRF for greatest transmitter range.



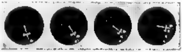
note The search radar is mounted in the highest practical position aboard ship. This location increases its line of sight range, and prevents shipboard masts from blocking the radar beam.

note

A target can be tracked on a P-Scope. Although this tracking is not accurate enough for fire control, it is sufficient for target evaluation.

A transparent overlay is placed on the scope. A marking is put over the first target indication. After another scan, the target is indicated in a new position which is marked. This procedure is continued to obtain a sufficient number of points to provide an accurate track of the target.

PLAN POSITION INDICATOR (PPI)



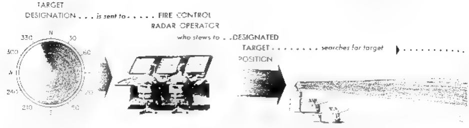
TARGET TRACKING ON A P-SCOPE

AND DESIGNATION

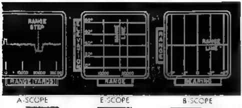

The number of fire control radars required in an installation depends on the number of weapons to be controlled. The number of search radars can also vary. A search radar may be especially designed for air search or for surface search. Or, as shown here, one radar may be used for both air search and surface search.

But, regardless of the particular installation, the system operation is the same. The target is first detected by the search radar, evaluated, and then designated to the appropriate fire control radar.

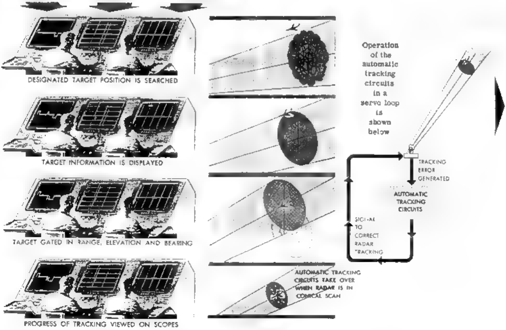
TARGET ACQUISITION



The radar beam is scanned in a spiral path to search a large area as the radar is slewed to the designated target position. If the target pip is not displayed with the radar at the designated position, the area is searched by simultaneously nodding the beam in elevation.



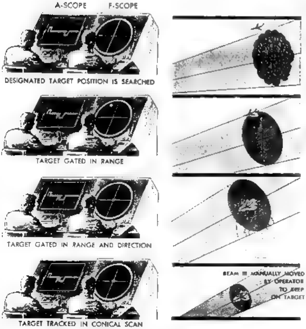
automatic tracking



If the target is not found, the bearing is changed to the right and to the left, continuing the nodding in elevation. If the target is still not seen, the operator then notifies the target designation center, and awaits more information on the target position.

A target may be tracked either manually or automatically. Procedures that are necessary to acquire, gate, and track a target by these means are now discussed.

manual tracking

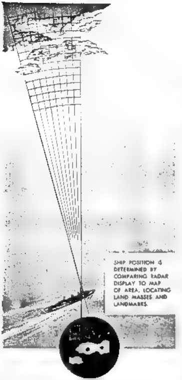


summary

Target designation information from the search radar is not precise. The fire control radar may be required to search around the designated position for the target. When the target acquisition is completed, the target may be tracked either manually or automatically. In manual tracking, the target is gated, and tracked manually. In automatic tracking, the target is gated manually, and tracked automatically.

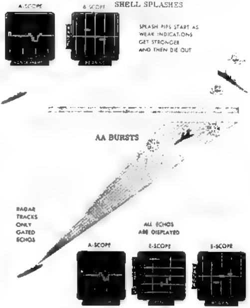
ADDITIONAL APPLICATIONS

navigation



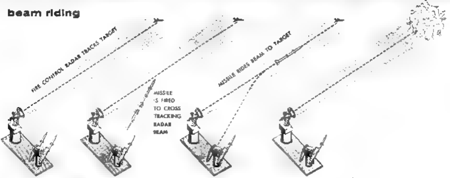
spotting

Shell splashes and AA bursts produce momentary echoes which are displayed on the radar scopes. Range, bearing and elevation spots can be estimated by the radar operator.



missile guidance

beam riding



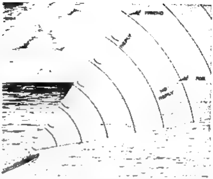
target identification radar-IFF

A pip on a radar screen can be evaluated to provide such information as target position, speed, direction and size. But it cannot provide information on whether the target is friend or enemy.

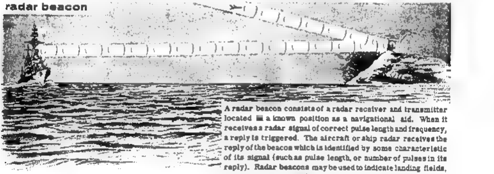
To overcome this shortcoming, an interrogation system —Identification, Friend or Foe (IFF) was developed. In this system, the IFF radar transmits a series of pulses arranged in a code, to challenge a target. Friendly ships and aircraft, equipped with IFF receivers and transmitters, receive the challenge and send back a coded reply.

Any target not replying to the challenge, or replying with the wrong code, may be evaluated as an enemy.

The reply code can be varied and, according to doctrine, may [redacted] changed at regular time intervals.

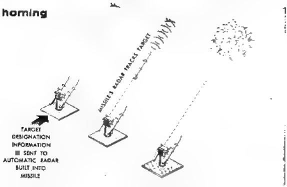


radar beacon



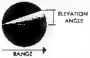
A radar beacon consists of a radar receiver and transmitter located [redacted] a known position as a navigational aid. When it receives a radar signal of correct pulse length and frequency, a reply is triggered. The aircraft or ship radar receives the reply of the beacon which is identified by some characteristic of its signal (such as pulse length, or number of pulses in its reply). Radar beacons may be used to indicate landing fields, mountains, or desired reference points.

homing



height-finding radar

Height-finding radar has the basic function of determining the height of an aircraft target. A beam sharply focused in elevation is vertically scanned. Using the range and elevation angle of a scanned target, the height is calculated and read on a calibrated dial or counter.



PROBLEMS

1. What are the advantages and disadvantages of a long pulse length in radar?

2. Design a fire control radar for directing missile fire against air targets in a range from 600 yards to 60,000 yards. The maximum duty cycle is not to exceed 0.001. The average power is not to exceed 100 watts.

   Design should include the following:

   (a) PRF
   (b) Pulse Length
   (c) Peak Power

3. What is the range discrimination of the fire control radar in problem 2.?

4.

A typical fire control radar would have the following design:		NOTE Circle answers that apply.	A typical search radar would have the following design:	
a	b	PULSE LENGTH (a) 0.5 μsec. (b) 3.0 μsec.	a	b
a	b	PRF (a) 200 (b) 2000	a	b
a	b	SCOPE TYPES (a) A and F (b) A and P	a	b
a	b	SCREEN PERSISTENCY (a) 0.5 millisec. (b) 2 sec.	a	b
a	b	DUTY CYCLE (a) 0.0006 (b) 0.1000	a	b
a	b	RANGE DISCRIMINATION (a) 50 yds (b) 500 yds	a	b

CHAPTER 6

SONAR

In World War II, submarines were responsible for sinking millions of tons of valuable shipping and the extensive loss of life. Since then, intensive research has greatly improved the capabilities and fighting potential of submarines. For example, nuclear-powered submarines have demonstrated speeds equaling that of many surface ships. They can travel submerged for long periods of time and over long distances, and are capable of underwater missile launchings.

To overcome this dangerous potential in enemy submarines, the best possible means of undersea detection is required. It must be fast operating because of high submarine speeds, and accurate to enable ASW fire control. Prior to World War II, underwater detection was accomplished by a system known as "listening". During the war sonar (Sound Navigation And Ranging) was developed. It met immediate needs, and has been improved with continuing development and operation. But to keep up with the rapid advances in submarine development, sonar must be further improved or a better underwater detection system must be developed.

Extensive research has been conducted and continues in Naval and private research laboratories to develop new and improved underwater detection means.

While the primary purpose of sonar is the detection of submarines, sonar has proven useful in navigation — detecting reefs, mines and other obstructions.

SCOPE OF CHAPTER

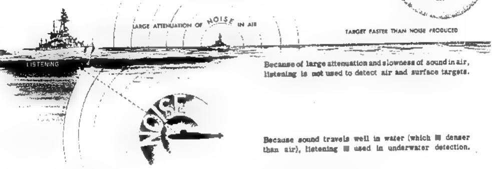
In this chapter, the basic principles of underwater detection by sonar will be discussed initially. Design features and limitations pertinent to sonar will be studied. The display of sonar information will be discussed and the general operation of a sonar system will be described to show its practical application.

principles

UNDERWATER DETECTION

listening principle

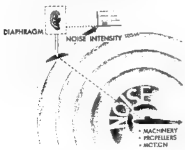
Targets may avoid optical detection under cover of night, fog, or smoke screens, or by operating underwater. While a target may travel hidden from sight, it cannot keep from making noise as it moves. By listening for this noise (which is sound energy) we can detect moving targets.

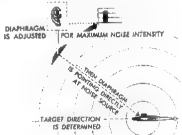


Because of large attenuation and slowness of sound in air, listening is not used to detect air and surface targets.

Because sound travels well in water (which is denser than air), listening is used in underwater detection.

A target may be detected by receiving target noise with a sensitive diaphragm underwater. Target direction may be determined with a diaphragm that is directional; that is, a type of diaphragm that receives the strongest signal when it points directly at the source of the noise.





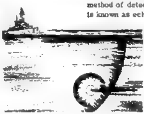
Listening is a passive method of detection, because it relies on target noise to detect the target. Listening gives long range detection (about 10 to 15 miles), and precise direction information on moving targets. However, listening cannot provide range information on moving targets, because the transit time of the noise cannot be measured; and listening cannot detect stationary targets which produce little or no noise.

WITH SOUND

echo ranging principle

To detect a stationary target, and determine the range of any target, an active method of detection is required. This is one in which the target is detected independently of any target action or condition.

An energy pulse is produced, and radiated by own ship. The radiated energy, striking a target, produces an echo which is received by own ship. This is an active method of detection, based on the echo principle, and is known as echo ranging.



Because own ship initiates the energy pulse and receives the echo, the transit time, and consequently the range, can be determined. The target direction may be determined in the same manner as in listening.

echo ranging with sound . . . SONAR

In the active system, energy is required to travel to the target as well as back (twice the distance as in the passive system). Range is limited by the attenuation of sound in the water, and the fact that only a small part of the energy is reflected as an echo. The range of the active system depends also on the maximum power of the pulse which is transmitted by own ship.

NOTE

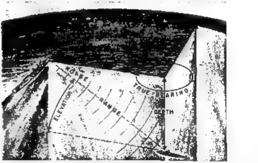
Listening is used by a submarine to accurately locate a moving surface ship. Knowing its own depth, and finding the elevation of the target noise, the submarine can compute the range of the target.

Echo ranging is not used by submarines for target detection because it reveals the submarine's presence. Echo ranging is used by submarines for navigation.

NOTE

In addition to the pulse transmission sonar noted, FM sonar, transmitting a continuous signal of varying frequency, has been developed. However, the sonars in operational use are almost completely of the pulse-type described in this chapter.

Radar energy and light energy are rapidly attenuated in water, and will not give sufficient range. Electronic design and water characteristics limit the maximum sound power that can be transmitted. The maximum range of the active system using sound energy is restricted to approximately five miles. This range is just sufficient in ASW fire control. Because a form of energy providing better operation is not present, sound is used in underwater echo ranging. Echo ranging with sound energy is known as sonar.



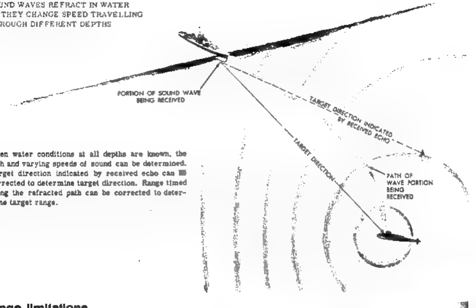
SUMMARY

After transmission, the echo ranging equipment uses the listening principle to receive any target echoes. Also, by using the receiving portion alone, the echo ranging equipment can detect target noise and, thereby, function as listening equipment.

PROPAGATION PROBLEMS

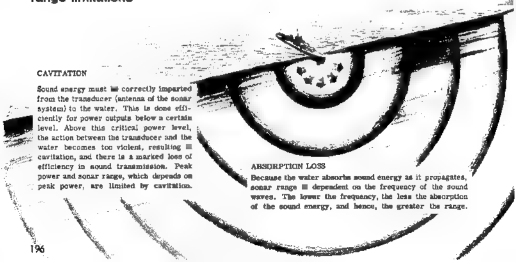
detection and tracking problem

SOUND WAVES REFRACT IN WATER
AS THEY CHANGE SPEED TRAVELLING
THROUGH DIFFERENT DEPTHS



When water conditions at all depths are known, the path and varying speeds of sound can be determined. Target direction indicated by received echo can [redacted] corrected to determine target direction. Range timed along the refracted path can be corrected to determine target range.

range limitations



CAVITATION

Sound energy must [redacted] correctly imparted from the transducer (antenna of the sonar system) to the water. This is done efficiently for power outputs below a certain level. Above this critical power level, the action between the transducer and the water becomes too violent, resulting [redacted] cavitation, and there is a marked loss of efficiency in sound transmission. Peak power and sonar range, which depends on peak power, are limited by cavitation.

ABSORPTION LOSS

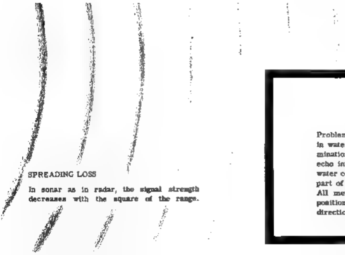
Because the water absorbs sound energy as it propagates, sonar range [redacted] dependent on the frequency of the sound waves. The lower the frequency, the less the absorption of the sound energy, and hence, the greater the range.

IN WATER

The advantages of water in sound propagation (density permits a detection range sufficient for ASW) enable the use of sound in underwater detection. The disadvantages of water in sound propagation will now be discussed.

Sound waves in water travel ■ about 4800 ft/sec. The time required for the echo to return from a range of 3 miles is about 3-3/4 seconds. With submarine speeds equaling that of surface vessels, target motion during the echo return must be considered in determining present target position.

Present target position ■ determined by considering the past position, speed and direction of target as supplied by sonar.



SPREADING LOSS

In sonar as in radar, the signal strength decreases with the square of the range.

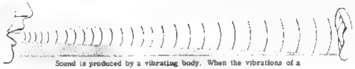
summary

Problems present in sound propagation in water have been discussed. Determination of present target position from echo information supplied by sonar and water condition data will be treated as part of the ASW fire control problem. All mentions of target direction and position in this chapter refer to echo direction and apparent target position.

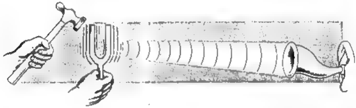
DESIGN

Because both use pulsed energy, the design features of sonar are similar to the design features of radar. The primary difference in the designs stems from the necessity to produce the sound energy and from the slowness of sound in water. The production of sound energy involves a different design from that used in the production of electrical energy in radar. The slowness of sound in water necessitates a difference from radar design in the method of energy transmission and reception. These design features are now discussed.

PRINCIPLES OF SOUND PRODUCTION

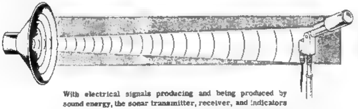


Sound is produced by a vibrating body. When the vibrations of a body can be controlled, sound transmission can be controlled. Vibrations of a body can be caused by mechanical means, but the strength and duration of the vibrations would be difficult to regulate. The use of mechanically-aided hearing to receive sound echoes is also impracticable.

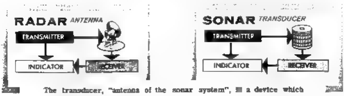


Electrical means also cause vibrations of a body. A loudspeaker uses electrical signals to produce vibrations of a diaphragm.

To receive the sound vibrations, a sensitive microphone can be used. The sound causes the diaphragm to vibrate, and the vibration produces electrical signals.



With electrical signals producing and being produced by sound energy, the sonar transmitter, receiver, and indicators can have designs similar to their counterparts in radar.



The transducer, "antenna of the sonar system", is a device which combines the principles of a loudspeaker and a microphone. The use of these principles in the design of a transducer is next discussed.

DESIGN OF TRANSDUCER

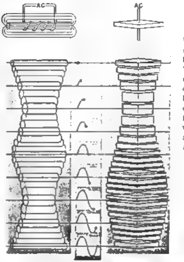
In a transducer, electrical signals can produce mechanical sound vibrations by two methods.

MAGNETOSTRICTIVE EFFECT

A rod, or tube, of ferromagnetic material (iron, nickel, etc.) will change in length when placed in a magnetic field. This is known as the magnetostrictive effect.

Then, if a nickel rod were placed in a continually varying magnetic field, its length would continually vary. Therefore, the rod will be vibrating. The frequency of the vibration is dependent on the frequency of the AC voltage applied.

The magnetostrictive effect also works in reverse. That is, when the rod is caused to vibrate by some outside source such as impinging sound waves, a varying magnetic field and AC voltage will be produced.



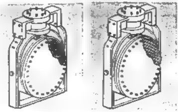
PIEZOELECTRIC EFFECT

When subjected to an AC voltage, some crystals will vibrate; this is known as the piezoelectric effect. The frequency of vibration of the crystal is dependent upon the frequency of the AC voltage applied. In a like manner, the piezoelectric effect also works in reverse. That is, when the crystal is caused to vibrate by some outside source such as impinging sound waves, an AC voltage is produced on its faces.

The rods are welded at one end to a steel plate (diaphragm). The combined vibration of the rods is then transmitted from the diaphragm.

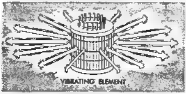
Some crystals are soluble, and must be kept from contact with sea water. The diaphragm and fluid used for this purpose are selected for the minimum change in sound (velocity and intensity) as it passes through.

When the rods or crystals are arranged in a flat array . . . .



. . . . the transducer transmits and receives directionally.

When the rods or crystals are arranged in a cylindrical array, the transducer transmits and receives omnidirectionally.



note

Certain electrical properties of crystals and magnetostrictive elements limit the amount of power output. When the applied voltage exceeds a critical value, a crystal breaks down, and the magnetostrictive effect ceases.

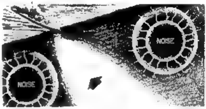
DIRECTIVITY OF SOUND BEAM

directional transmission

By transmitting the energy in a narrow beam, the sonar has a greater range than if the same amount of energy were transmitted in all directions.
However, with narrow focusing of the sound energy, only a small angle is searched with each transmitted pulse. Because of the slowness of sound in water, it takes about [illegible] seconds for sound energy to travel to and return from a range of 2 miles. If 5 degrees were searched by each transmitted pulse, at least 6 minutes would be required to perform a complete 360-degree search.

directional reception

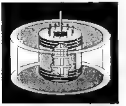
In directional reception, the transducer is focused to receive sound energy primarily from one direction. Sound energy from other directions is poorly received, and not indicated by the sonar.
Thus, noise produced at other directions can not mask an echo returning along the receiving direction.



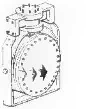
note The original sonar (searchlight sonar) was designed with directional transmission and directional reception. The disadvantage of the excessive time required for a complete search led to the development of the scanning search sonar.

scanning search sonar

At the close of World War II, scanning search sonar was developed which combined the desirable features of omnidirectional transmission, and directional reception.



Omnidirectional transducers transmit a pulse in all directions. Each returning echo must be received directionally to distinguish one echo direction from another. A directional receiving path, such as that of the searchlight transducer, must be rapidly scanned in order to receive all echoes, regardless of their directions.
However, because rapid transducer movement in water is not mechanically feasible, the searchlight transducer can not be used in scanning directional reception.



Just as the antenna design determines the focusing of the radar beam, the transducer design determines the focusing of the sound beam. If a transducer transmits and receives primarily in a narrow beam, it is directional; if it operates equally in all directions, it is omnidirectional.

omnidirectional transmission

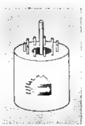
With omnidirectional transmission, a 360-degree search is accomplished with each transmitted pulse. All targets in the range of the sound are hit by each transmitted pulse.

note

Sonars usually have provision for several different pulse lengths (pings) selected at the discretion of the operator. For example, the operator may use a long pulse length (30 or 80 milliseconds) for initial target detection and a short pulse length (6 milliseconds) for target tracking. Longer pulse lengths provide greater range while shorter pulse lengths provide better discrimination.

omnidirectional reception

An omnidirectional transducer, receiving equally from all directions, is not able to determine the direction of one echo from the direction of another echo. Noise received from the sea, other than target noise and target echoes may mask target noise or target echoes.



The equivalent of mechanically scanning a searchlight transducer for directional reception can be performed inside the omnidirectional transducer by electronic means.

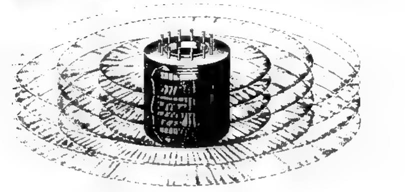
Thus, the scanning search sonar uses the omnidirectional transducer for both omnidirection transmission and scanning directional reception.

summary

It is now seen that omnidirectional transmission and directional reception are used in scanning search sonar. In the following pages, the principles of directional reception, and the design of the omnidirectional transducer to enable directional reception, will be discussed.

THE SCANNING SONAR TRANSDUCER

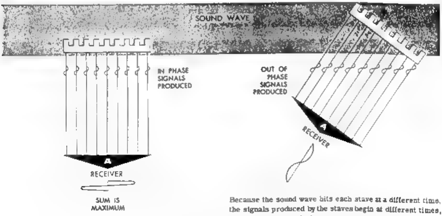
The scanning search sonar is the main type used in underwater detection. It has replaced the searchlight sonar which may still be found in harbor defense, and on some reserve ships. The principles of directional reception with a flat array (searchlight sonar) is first discussed. The design means used to make the omnidirectional transducer (scanning search sonar) operate equivalently is then shown.



directional reception by searchlight transducer

The searchlight transducer uses a flat array to determine the direction of received echoes. When the array is adjusted for maximum echo signal, the signals produced by the staves are in phase, producing the maximum sum at A.

When the array is not pointed directly at the sound wave (inclined to the wave front), the signals produced by the staves are out-of-phase, producing a sum at A which is less than the maximum.



Because the sound wave hits each stave at a different time, the signals produced by the staves begin at different times, and thus, are out-of-phase.

Target direction is determined by adjusting the transducer for maximum sum at A, and noting the direction of the transducer.

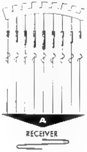
directional reception by omnidirectional transducer

The curved array shown is a portion of an omnidirectional transducer. A sound wave hitting it directly, or at any angle, produces out-of-phase signals.

SOUND WAVE

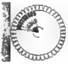
DELAY CIRCUITS

If all the signals produced were in phase when the sound wave directly hit the center of the array, the curved array would be equivalent to a directional transducer. To accomplish this, delay circuits are inserted in the lines to alter the phase of the signals. These delay circuits are designed so that when the sound wave directly hits the center of the array, in-phase signals are produced by the staves.



THE SCANNING SWITCH

Thus, any portion of the cylindrical transducer can be made directional by the use of these delay circuits. To scan the entire area around the ship, the delay circuits are connected to rotating contacts instead of directly to the staves. These rotating contacts comprise the scanning switch.



To receive echoes regardless of their directions and times of reception (ranges) the scanning switch must rotate at least once in the pulse length time.

The contacts rotate, continually connecting a different set of staves to A. In this manner, the equivalent of mechanically scanning a flat array is accomplished electrically inside the omnidirectional transducer.

When the transducer is oriented so that the scanning switch moves in a horizontal plane, directional reception in bearing is accomplished. When the transducer is oriented so that the scanning switch moves in a vertical plane, directional reception in depression is accomplished. To determine target position, the scanning search sonar requires two scanning transducers. Either transducer can be used to determine target range.

DISPLAY OF INFORMATION

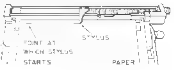
In radar, the type of display is determined by the purpose of the radar such as, F-Scope for AA fire control radar, P-Scope for search radar, B-Scope for surface fire control radar, etc. Since the same sonar equipment is used for both search and fire control, the number of different range displays and direction displays are less in sonar than in radar. The range and direction displays used in sonar are now discussed.

range

Range display requires a means of visually determining echo transit time. As seen in Radar, there are two requirements for determining echo transit time:

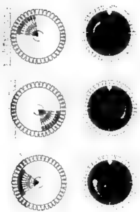
1. Time sweep (indicator which moves at a constant speed over a known interval of time).
2. Marking transmitted and received pulses on the time sweep.

Because the intervals timed in sonar are in the order of a few seconds, mechanical devices such as the range recorder, can be used for determining echo transit time.



direction

Direction information can be displayed on a CRT. The light trace on an electromagnetic CRT is made to rotate as the scanning switch rotates. When an echo is received, target direction is indicated on the screen.



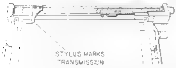
Range information can also be displayed on the same screen by applying a range sweep voltage to the magnetic deflection coil of the electromagnetic CRT. The range of a target is indicated as the radial distance of the target pip from the center of the screen. Because separate scanning transducers are required for determining bearing and depression angle, separate displays are also required. A sonar usually has both a bearing and range display and a depression angle and range display.

note

The scanning sonar transducer does not operate efficiently over the larger depression angles. The sonar may lose contact with the target at short ranges and large depression angles. To compensate somewhat for this, a feature, known as MCC (maintenance of close control), permits the operator to depress the sonar beam and thus, maintain contact over the large depression angles. This feature is not used continuously because it distorts the sound beam at long ranges.

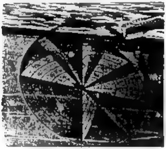
In the mechanical range recorder, a stylus (electric pencil) is mechanically swept across a paper at a constant speed for a known interval of time. This comprises the time sweep.

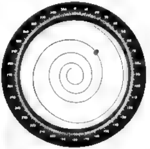
At transmission and reception, an electrical signal is applied to the stylus, causing an indication on the paper.



Several range scales, such as 1000, 3000 and 6000 yards, are usually provided on the range display. Because of the slowness of sound, the shortest possible range scale is used when tracking a target.

bearing and range

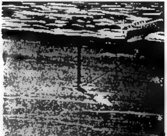


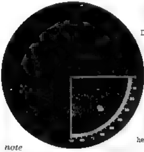


To display 360 degrees of bearing and range, a P-Scope is used.

The combined effect of bearing sweep and range sweep causes the light trace to sweep a spiral path on the screen.

depression angle and range





Depression angle of the target is measured with respect to the water surface. The depression angles of 0 to 90 degrees are displayed on a screen similar to that used in height-finding radar.

note

Because the time between successive transmissions depends on the maximum range being searched, the PRF is not a set, designed value as in radar. The sonar operator manually triggers each transmission.

LIMITATIONS

BACKGROUND NOISE

transducer frequency

Echo ranging sonar transmits sound at one frequency. Because a high frequency allows a small transducer design, the frequency used in early transducer design was in the ultrasonic range (about 24kc). The transducer is tuned to receive sound at and about this designed frequency.

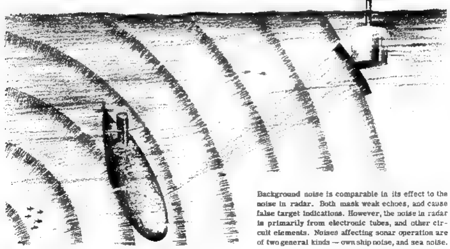
Listening equipment depends on receiving target noise. Propellers, engines, pumps, gear wheels, rudder motors, and other devices produce sonic sound (below 15kc). High speed propellers produce ultrasonic sound. A listening transducer may be tuned to receive the large volume of low frequency sound produced by a target, or it may be broadly tuned to receive both sonic and ultrasonic sounds.

An echo ranging transducer also used for listening purposes must be broadly tuned to receive sound in the low frequency (target noise), and in the high frequency (echo).

interference with reception

A transducer can not distinguish between echoes and noise produced by a target, and noise produced by other sources. When this noise is in the frequency range of the transducer, it is received as readily as target noise and echoes. The noise from other sources, known as background noise, may appear to be target noise, or it may mask a target echo on the sonar indicator.

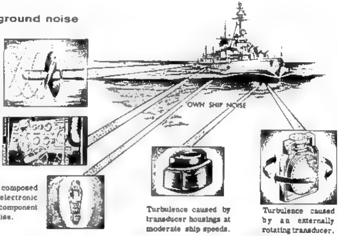
Since most of the background noise can not be prevented, the operator must learn to recognize and effectively operate with it.



Background noise is comparable in its effect to the noise in radar. Both mask weak echoes, and cause false target indications. However, the noise in radar is primarily from electronic tubes, and other circuit elements. Noises affecting sonar operation are of two general kinds — own ship noise, and sea noise.

Limitations in tracking due to sound refraction and slowness, were discussed in SOUND PROPAGATION IN WATER. In addition to these, sonar has operational limitations due primarily to background noise, and reverberations. Because the effect of these limitations on operation is dependent on the sonar frequency, the frequency of the transducer is initially discussed.

sources of background noise



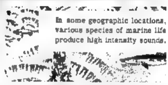
Noise from propellers and machinery is prominent, because of its proximity to the transducer.

Circuit noise, composed primarily of electronic tube noise, is a component of background noise.

Turbulence caused by transducer housings at moderate ship speeds.

Turbulence caused by an externally rotating transducer.

Wave motion at the surface of the water produces a large ambient noise level.



In some geographic locations, various species of marine life produce high intensity sounds.

Traffic noise, resulting from a large number of ships operating in a small area, may be high in a harbor.

Surface noises, such as that from gunfire and aircraft, add to the level of background noise.

note

Because of the relatively short ranges of sonar, and wide intervals maintained between submarines, discrimination is not an important factor in pulse length design.

SUMMARY

Background noise, which can mask target echoes and target noise, is produced by a variety of sources. For this reason, background noise may have different intensities over a wide frequency range. The interference caused by the background noise depends on the frequency range of the receiver, and the frequency of the transmitted sound.

Background noise is not the only consideration in the masking of target information. Reverberation, which masks target information in echo ranging sonar, is discussed in the following pages.

REVERBERATION

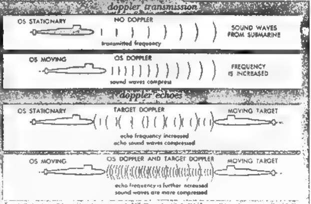
All objects in the path of the transmitted sound wave produce echoes. Fish, air bubbles, marine growth, suspended particles, the water surface, and bottom reflect and scatter the sound energy, producing what is known as reverberation.

While each of these sources may not produce an appreciable echo by itself, reception of them at the same time by sonar produces a continuous echo of high intensity.

THE DOPPLER PRINCIPLE

The Doppler principle states that frequency of sound appears to increase when an observer moves toward a source, and appears to decrease when he moves away from it.

This change of frequency is evident in underwater detection. Change in frequency due to the movement of own ship is known as Own Ship Doppler. Change in frequency due to the movement of the target is known as Target Doppler. If the echo frequency is greater than the transmitted frequency, it is called Up Doppler; if the echo frequency is less, it is called Down Doppler. These differences in frequency can normally be detected by the human ear.

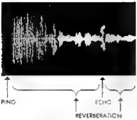


When two objects are approaching each other, the echo frequency will be greater than the transmitted frequency.

It could also be similarly shown:

When two objects are getting farther apart, the echo frequency will be less than the transmitted frequency.

When there is no relative motion in range between the two objects, the echo frequency is the same as the transmitted frequency.



To distinguish echoes from reverberation, and to aid in evaluating scope pips, the target information is presented audibly as well as visually. This is accomplished by using an audio scanning switch in addition to the video scanning switch previously discussed. The audio scanning switch channels received sound through circuitry to a loudspeaker.

The CRT oscilloscope is unable to distinguish between noise, echoes and reverberations. The scope simply displays a pip for a certain magnitude of signal input, regardless of whether the input is caused by echoes, noise, or reverberations, or a combination of these sounds.

When the audio scanning switch is manually rotated to the echo bearing, target echoes, converted into audible sounds, are heard over the loudspeaker. However, reverberation is also heard over the loudspeaker.

By application of the Doppler principle, the sonar operator can audibly distinguish between target echoes and reverberation. The Doppler principle will be discussed next, followed by a discussion of its application in sonar.

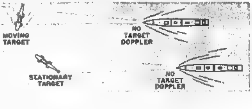
application

Reverberation is caused almost completely by stationary objects. Therefore, the frequency of reverberation will be the transmitted frequency plus Own Ship Doppler. An echo from a target will have a frequency determined by transmitted frequency, Own Ship Doppler, and Target Doppler. Therefore, if the target is moving with respect to own ship, the echo frequency will be different from the reverberation frequency. The difference between the two is the Target Doppler.

Since the echo has a different pitch than the reverberation, the ear can distinguish between the two. Reverberation is heard immediately after transmission, and continues for a while as it fades in intensity. Sound of a different pitch may be easily distinguished from the reverberation background. The faster the target moves, the greater will be the pitch difference, making it easier for the ear to distinguish. Even a weak sound can be distinguished from others which are strong if the pitch difference is large.

limitation

When the target is stationary, or moving at right angles to own ship, there is no Target Doppler. In this case, the echo frequency is the same as the frequency of the reverberation, and the echoes may be masked audibly as well as visually.



summary

When the frequency difference between echo and reverberation is large, reverberation is a wanted sound, because it enables the operator to determine Target Doppler.
When the frequency difference is small, reverberation is an unwanted sound, because it masks the target echoes.
The importance of Doppler and the audible presentation of echoes in target evaluation is discussed in the following pages on SYSTEM OPERATION.

SYSTEM

Sonar systems do not have individual equipment for search and fire control operations as we have seen in radar. Instead, there is an operating procedure when using the equipment for search, and another operating procedure when using the equipment for

TARGET

The video presentation, which indicates targets in a 360-degree scan, and the audio presentation, which indicates targets in a narrow beam width, are the two methods of initial target detection in sonar. While the video scanning switch is covering the full 360 degrees, the sonar operator manually searches the area with the audio scanning switch. A set pattern is followed in order to cover the full 360 degrees in the audio search.

TARGET

When the echo may be a submarine, its bearing and range are reported immediately to the CIC. After the report of sonar contact, the operator makes a preliminary determination of the nature of the contact. It is the sonar operator's job to secure all information which will aid in target evaluation. From the video and audio presentations, the following target evaluations, in addition to position, are made.

Target range rate, estimated from the doppler, can be determined with each echo. Without doppler, target position would have to be plotted to determine range rate.

Target aspect is determined from doppler, echo quality, and target width. There are five standard target aspects:

Absence of doppler would indicate a beam target. Up Doppler indicates a low or direct bow target, and Down Doppler indicates a quarter or stern-on target.
The echo from the bow of the target is usually clear and sharp in quality. The echo from the stern is usually mushy, because it is combined with echoes from the target wake.

TARGET CLASSIFICATION

There are four classifications of an underwater target: positive submarine, probable submarine, possible submarine, and non-submarine. With any of the first three classifications, the target will continue to be tracked and evaluated by the sonar operator. The evaluation information will continue to be sent to CIC, because it may warrant reclassification of the target.

OPERATION

tracking. Operation of a sonar system depends more upon ship doctrine than does the operation of a radar system. The basic elements in the operations of a sonar system, are: target detection, target evaluation, target classification, and target tracking.

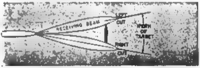
DETECTION

PIP SUSPECTED TO BE SUBMARINE

Because noise and reverberation are usually displayed in different positions on successive sweeps of the video scanning switch, the screen should be watched for a few sweeps, to determine if a pip indicates a submarine. When the pip repeats itself, and has the characteristics of a submarine echo, the echo is investigated by the audio scanning switch. If investigation indicates that the pip is not caused by a submarine, the audio search is resumed.

EVALUATION

Target width is determined by observing the bearings at which echoes are not received as the audio scanning switch is moved off the target to the right, and to the left. This is known as taking "cuts" - left cut off left side of target, and right cut off right side of target.



Target evasive action indicates that the target is a submarine, and is aware it has been detected. A radical increase in submarine speed produces excessive noise which may mask the echo. By noting the target echo in relation to the target noise on the screen, changes in target aspect can be obtained.

Target maneuvering is noted from a plot of past target positions, but it is more rapidly indicated by doppler. Target maneuvering is checked for compatability with submarine characteristics.

AND TRACKING

During the tracking, the target bearing is obtained by taking "cuts" and using the middle of these two bearings as the target bearing. The more cuts that can be performed with accuracy, the more precise will be the tracking of the target.

Note

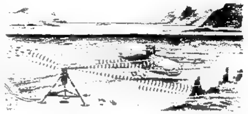
A sonar may be considered to consist of search and fire control equipments. The scanning transducer for determination of bearing and range provides for the initial target detection. The addition of a scanning transducer, for determination of depression angle comprises the fire control equipment.

OTHER SONAR INSTALLATIONS

Sonar equipment is not limited to use on surface ships and submarines. There are other installations of sonar used by the Navy in underwater detection.

HERALD

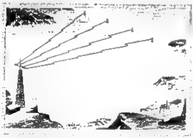
The herald is a searchlight-type transducer which is mounted on a tripod planted on the bottom of the sea. Target information is sent from transducer to detection station on shore by a submarine cable. At the detection station, the transducer can be set to automatically search a particular section, or can be trained manually. The herald is used mainly in permanent installations, such as in harbor defense.



SONOBUOY

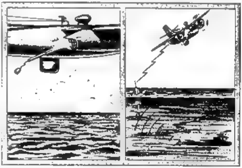
Sonobuoy, is a listening equipment installed in a buoy, which detects underwater sounds, and radios the information to a control station. The control station can be located on shore, or in an aircraft.

Sonobuoys may be used in temporary harbor defense installations at advance bases.



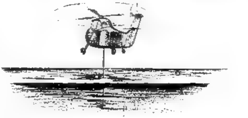
Large areas of water can be searched quickly by

dropping sonobuoys into the open sea, and using an aircraft control station.



HELICOPTER SEARCH

A sonar transducer, mounted on the end of a cable, is installed in a helicopter. To search for submarines, the helicopter can hover over a suspected area, and lower the transducer into the water. Because of its speed, maneuverability, and ability to hover, the helicopter can search large areas in a much shorter time than a sonar equipped vessel.



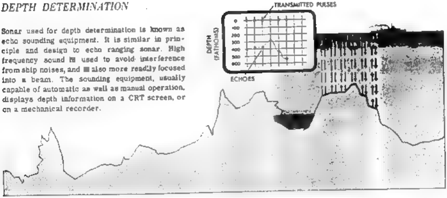
AND APPLICATIONS

In addition to its use in submarine detection, sonar has many other important applications.

NAVIGATION Surface vessels and submarines use sonar as an aid to navigation by warning of reefs, submerged rock formations, icebergs, and other underwater obstacles.

DEPTH DETERMINATION

Sonar used for depth determination is known as echo sounding equipment. It is similar in principle and design to echo ranging sonar. High frequency sound is used to avoid interference from ship noises, and is also more readily focused into a beam. The sounding equipment, usually capable of automatic as well as manual operation, displays depth information on a CRT screen, or on a mechanical recorder.



COMMUNICATION

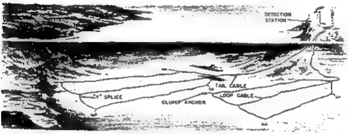
Communication in water can be accomplished by modulating sound waves in a manner similar to modulating electronic waves in radio broadcasting. Communication, which may be in either voice or morse code, has been established between points more than six miles apart.

UNDERWATER MAGNETIC DETECTION

To supplement sonar under certain conditions, a method of underwater detection using the magnetic properties of submarines was developed. However, because there may be many objects of magnetic properties underwater (mines, shipwrecks, etc.), magnetic detection can not, by itself, sufficiently establish the presence of a submarine. Magnetic detection is used in conjunction with sonar to initially detect a suspected target, or to verify a sonar contact.

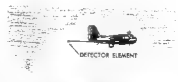
magnetic indicator loop

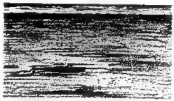
The magnetic indicator loop is a fixed underwater system designed to initially detect vessels, either surface or underwater. Loops of cable, laid on the ocean bottom, pick up any distortion of the earth's magnetic field caused by the presence of a ferromagnetic body over the loops. A fluxmeter, connected to the ends of a set of cables to indicate the distortion of the magnetic field, is located at the detection station ashore.



magnetic airborne detector . . . [MAD]

Magnetic detection equipment may be mounted on an aircraft. When the equipment enters a magnetic field, such as that produced by a surface vessel or submarine, an indication is noted on the MAD equipment. In an aircraft, the detector element is mounted as far as possible from the field of the ship.





Introduction to GYROS

- basic gyro
- functions of gyro devices

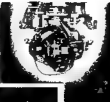
A gyro is the modern, scientific counterpart of an ancient toy — the spinning top. It is a remarkable fact that tops existed centuries before the Christian era, but the theory of the modern gyro was not written before 1765 and the first gyro was actually made after 1800. The term "gyroscope" was coined in 1852 by Foucault, who used one to demonstrate the earth's rotation. His gyro was not motor-driven; it was set in motion by a gear train. Throughout this century, the gyro remained a scientific toy.

Only in the past few decades has the gyro been used in instrumentation. From its crude beginnings it has developed into a formidable instrument of precision, used in gun sights, stabilizers, gyro compasses, and other devices important in fire control. A great advance has been made by combining gyros with follow-up systems, which enable a small gyro to control a heavy load.

SCOPE OF THIS CHAPTER

This chapter is divided into two sections. The first section explains the principles of the basic gyro and mathematically derives the law of precession, which is followed by the law of gyro reaction. The second section discusses the functions of gyro devices under two headings: constrained gyro (rate and integrating gyro) and free

gyro compass used in naval equipment.



SECTION 1

BASIC GYRO

A rapidly spinning top stands up and does not fall down. A rapidly turning hoop can roll along the ground without falling over. Such phenomena are due to certain peculiarities of a spinning object. These are known as "gyroscopic" effects, and a wheel made to spin, with the object of using these effects is known as a "gyro".

This chapter ■ a survey of gyros - what they are, why they behave the way they do, and how they are used in fire control.

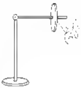
Gyros have a number of important functions in naval ordnance, such as stabilization, measurement of rates, integration, and guidance control. We shall describe some of these functions in the second section of this chapter.

This, the first section, will present basic facts about the gyro. In the course of this exposition we shall introduce and explain some peculiar properties of the gyro.

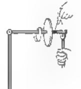
A simple classroom experiment, shown in the sketches at the right.

Wheel fixed to shaft connected to vertical support. Shaft hung from support.

Sha't (non-spinning) shown supported in a horizontal position.



Shaft released, drops to original hanging position.



String wound on shaft ■ pulled, causing shaft and wheel to spin.

Spinning shaft remains horizontal and turns around vertical support. This movement is called "precession".

Another experiment which shows the same phenomenon.

A classroom gyro, supported through its center of gravity, has a weight suspended on its spin axis.

Gyro is not spinning; hand is supporting the axis in a horizontal position.

Gyro is not spinning; hand is removed; therefore gyro topples over.

Gyro is spinning; hand is removed; gyro precesses; does not topple over.

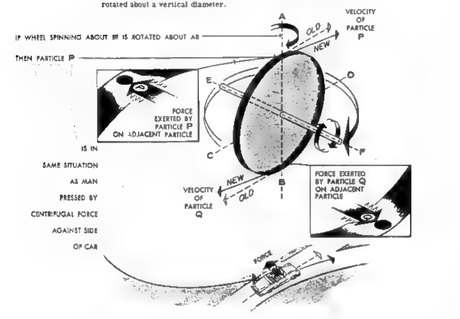
. . . this gyro phenomenon and others will now be discussed.

PRECESSION

In the introduction we had a glimpse of one of the oddities of gyro behavior. Why should the gyro with a weight on its spin axis turn around instead of toppling over? The answer is "precession". The weight causes a torque on the gyro: owing to the torque, the gyro precesses. We expect a force to cause an acceleration. Here it seems to be causing a constant velocity.

Why? The answer is that a constant ANGULAR velocity conceals an acceleration. A stone whirled around in a circle at the end of a string is actually accelerating toward the center of the circle. A spinning wheel, in precessing about a vertical axis, is actually accelerating about a horizontal axis.

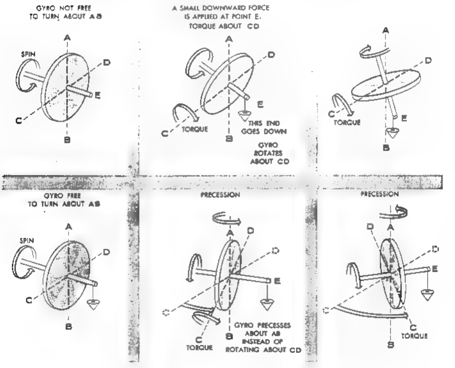
This becomes easier to visualize if we consider the case in reverse. Consider what happens when a spinning wheel with a horizontal axis is rotated about a vertical diameter.



A particle at the top of the wheel presses against an adjacent particle with a force acting away from us. The same thing is true to a lesser extent of other particles above CD. A particle at the bottom of the wheel presses against an adjacent particle with a force acting toward us. The same thing is true of other particles below CD. The effect of all these forces is a TORQUE tending to rotate the wheel about CD-counterclockwise looking from C to D. Just as the man in the car will be shot out if the door is open, so the gyro, if unrestrained, will topple over. In general, if you turn a spinning wheel about a diameter, it will try to turn about another diameter. If the gyro is restrained by a spring, the torque can be measured by the stretch of the spring. Just as the pressure exerted by the man against the side of the car increases if he becomes heavier, or the car goes faster, or turns faster, so does the torque on the wheel increase with the weight of the wheel, rate of spin, and rate of applied rotation. The stretch of the spring can be measured to compute the rate of applied rotation, if the other quantities are known.

This is only a loose and qualitative picture of what is happening, but it lends plausibility to one of the oddities of gyro behavior. We shall now become more precise.

Just as applying rotation about the vertical diameter to a spinning wheel causes a torque about the horizontal diameter, so does applying a torque about the horizontal diameter cause rotation (precession) about the vertical diameter. Let us consider, in detail, what happens when a weight is hung on the (horizontal) axle [illegible] a spinning wheel that is: 1 - not free to precess. 2 - free to precess. (This is the "classroom gyro" experiment shown in the introduction.)



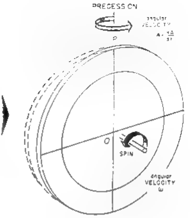
The cause of precession is the applied torque. Why this is so can be shown most easily if we assume that precession does take place and ask ourselves what forces would produce such a rotation.

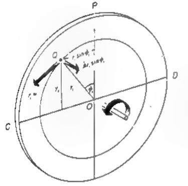
First, we must mention a convenient mathematical shorthand that we shall adopt, because it saves time. When we say: "If quantity x [illegible] infinitesimal, event y occurs" we mean: the smaller the quantity x becomes, the more nearly does event y occur. Another shorthand way of saying this [illegible]: "In the limit, as x approaches zero, y occurs". We must not consider x BECOMING zero too soon or our equation would become meaningless; consider it as APPROACHING zero. This [illegible] the principle of limits, and is the foundation of the differential calculus.

For the sake of simplicity, the derivation of the law of precession we are about to give applies only to a THIN disk. Actually it is close enough for any gyros encountered in practice.

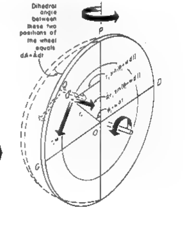
BASIC CONSIDERATIONS

Suppose that the wheel is spinning with angular velocity ω radians/sec. about the spin axis at O, and precessing with angular velocity $\dot{A}$ about vertical axis OP ($\dot{A} = dA/dt$).





A particle of mass m_1 (not necessarily on the rim) is at point Q at the beginning of infinitesimal time interval dt. Point Q is at a distance r_1 from O, making an angle ϕ_1 with OP. Thus, Q is at a distance $r_1 \sin \phi_1$ from OP, and at a distance that is $r_1 \cos \phi_1 = y_1$ from horizontal axis CD. The particle has two velocities: 1) $r_1\omega$ due to spin, and 2) $\dot{A}r_1 \sin \phi_1$ due to precession. These velocities are at right angles; the one due to precession is horizontal.

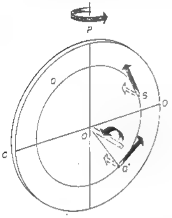


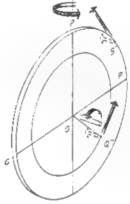
During time interval dt, the wheel spins through angle ωdt, thereby increasing ϕ_1 to $\phi_1 + \omega dt$; it also precesses through angle $\dot{A}dt$. As a result of these two motions, the particle is now at Q'. Not only its position but its two velocities have changed. The velocity due to spin is still $r_1\omega$, but its direction has changed. The velocity due to precession has increased from $\dot{A}r_1 \sin \phi_1$ to $\dot{A}r_1 \sin (\phi_1 + \omega dt)$; also its direction has changed. The spin velocity vector at Q is swung COUNTER-CLOCKWISE (looking from Q toward O) when the particle moves to Q'. The precession velocity vector is lengthened because Q' is farther from OP than Q is. Both effects are due to a force pointing TOWARD US.

PRECESSION

The spin velocity at S is swung counterclockwise (looking from S to O) when the particle moves to S'. The precession velocity vector is shortened because S' is closer to OP than S is. Evidently all particles above CD are acted on by forces pointing TOWARD US.

The spin velocity vector at Q'' is spun clockwise (looking from Q'' to O) when the particle moves to Q'''. The precession velocity vector is lengthened. Evidently all particles below CD are acted on by forces pointing AWAY FROM US.





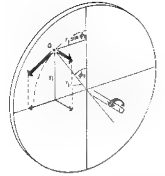
These changes in velocity constitute an ACCELERATION, which must be due to a FORCE. The only force that concerns us is horizontal and, in addition, perpendicular to the plane of the wheel. Other forces would tend to compress the material of the wheel or accelerate the spin, and we know that neither of these events occur.
This all adds up to a torque about CD, clockwise looking from C to D. The only other mode of rotation the wheel has (apart from its spin) is about OP. But the torques about OP cancel out, because every particle on the left side of OP has its "image" on the right side, and they are acted on by forces in the same direction.

To sum up: Consider the forces on all the particles in the wheel that are horizontal and, in addition, perpendicular to the plane of the wheel. When we have added together their torques about CD we shall have the total torque producing precession.

We shall now derive the mathematical formula of precession:

$$T = I\omega\dot{A}$$

where T = torque
ω = angular velocity of spin
$\dot{A}$ = angular velocity of precession

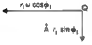


MATHEMATICAL ANALYSIS

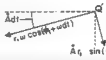
Let dV be the significant change in velocity, i.e. the change in velocity perpendicular to the plane of the wheel. Then dV/dt = acceleration, and $m_1(dV/dt)$ = force on particle producing this acceleration.

To obtain dV, we obtain the components of the horizontal velocities at Q and Q' perpendicular to the plane of the wheel at Q, then subtract the components at Q from the components at Q'.

PROJECTION OF VELOCITIES AT Q ONTO A HORIZONTAL PLANE



HORIZONTAL COMPONENTS OF VELOCITIES AT Q AS SHOWN ABOVE



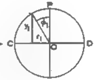
HORIZONTAL COMPONENTS OF VELOCITIES AT Q' AS SHOWN ABOVE LEFT

EVALUATION OF TORQUE

We now add the velocity vectors dV' and dV'' to obtain the torque, substituting the values just obtained.

$$dV = dV' + dV''$$
$$= r_1\omega \cos\phi_1 \cdot \dot{A}dt + \dot{A}r_1 \cos\phi_1\, d\phi_1$$

$$\text{Acceleration} = dV/dt = dV'/dt + dV''/dt$$
$$= r_1\omega \cos\phi_1 \cdot \dot{A} + \dot{A}r_1 \cos\phi_1\, (d\phi_1/dt)$$
$$= r_1\omega \cos\phi_1 \cdot \dot{A} + \dot{A}r_1 \cos\phi_1 \cdot \omega$$
$$= 2\dot{A}\omega r_1 \cos\phi_1$$
$$= 2\dot{A}\omega y_1$$



$$\text{Force} = \text{mass} \times \text{acceleration}$$
$$= 2m_1\dot{A}\omega y_1$$

$$\text{Torque about CD} = \text{force} \times y_1$$
$$= 2m_1\dot{A}\omega y_1^2$$
$$= 2\dot{A}\omega \cdot m_1 y_1^2$$

This is the torque due to the force on the particle at Q, with mass m_1 distant y_1 from CD. The whole wheel consists of particles with masses m_1, m_2, m_3, ... whose distances from CD are y_1, y_2, y_3, ...

$$\text{Torque on whole wheel about CD} = 2\dot{A}\omega(m_1y_1^2 + m_2y_2^2 + \ldots)$$
$$= 2\dot{A}\omega I_a$$
$$\text{where } I_a = \text{moment of inertia about CD}$$
$$= (1/2)I$$
$$\text{where } I = \text{moment of inertia about spin axis}$$
$$\text{So torque} = T = I\omega\dot{A}$$

Express ω and $\dot{A}$ in radians per second.

If I is in pound-feet squared, then T will be in poundal-feet. To obtain T in pound-feet, divide by g (32.2 at sea level). To evaluate I (M being the mass in pounds): For a uniform disk: $I = (1/2)Mr^2$. For a disk with most of its mass near the rim, $I = kMr^2$, where k is between 1/2 and 1.

Horizontal spin velocity vector $r_1\omega \cos \phi_1$ and horizontal precession velocity vector $\dot{A}r_1 \sin \phi_1$ both change in magnitude and direction. However, in the case of the spin velocity vector we need consider only the change in direction; in the case of the precession velocity we need consider only the change in magnitude.

This is because the change in magnitude of $r_1\omega \cos \phi_1$ and the change in direction of $\dot{A}r_1 \sin \phi_1$ are due to forces not perpendicular to the plane of the wheel. (Incidentally they only introduce negligible second-order infinitesimals.)

Let dV' = change in velocity due to change in direction of $r_1\omega \cos \phi_1$
dV'' = change in velocity due to change in magnitude of $\dot{A}r_1 \sin \phi_1$

Since dV' and dV'' are in the same direction (perpendicular to the plane of the wheel), they can be added numerically.

Total change in velocity
$= dV = dV' + dV''$

To obtain dV', consider change in direction of $r_1\omega \cos \phi_1$
$dV' = r_1\omega \cos \phi_1 \dot{A}dt.$

To obtain dV'', we simply differentiate $\dot{A}r_1 \sin \phi_1$:
$dV'' = d(\dot{A}r_1 \sin \phi_1) = \dot{A}r_1 \cos \phi_1\, d\phi_1$. ($\dot{A}$ and r_1 are constants.)

We have now obtained the required horizontal velocity vectors.

The equation $T = I\omega\dot{A}$ applies only to cases where spin and precession are about mutually perpendicular axes. For the present, these are the only cases we shall consider. For other cases, there is a more complicated equation which reduces to the simpler one with increasing rate of spin.

Now we see why the wheel does not topple over. We have shown that the precession velocity $\dot{A}$ accounts for all of the applied torque $I\omega\dot{A}$. Hence, there can be no other motion of the wheel, except spin.

The equation $T = I\omega\dot{A}$ tells us that the torque required to produce a given precession is directly proportional to the rate of spin and the rate of precession. Transposing, we obtain: $\dot{A} = T/I\omega$. This tells us that rate of precession is directly proportional to torque but inversely proportional to rate of spin. The faster the spin, the slower the precession.

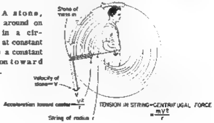
The sense in which the torque acts - clockwise looking from C to D - gives us the "law of axes" discussed further on. Every particle has two forces acting on it, one which rotates the spin velocity vector and one which expands or contracts the precession velocity vector. With regard to the former:

If dt is infinitesimal, the change-in-velocity vector, and hence the acceleration, is perpendicular to the spin velocity vector. (By "acceleration" we mean that portion of the total acceleration which is due to the rotation of the spin velocity vector.)

If the acceleration persisted for a finite time in the same direction, the velocity would change in magnitude.

But this does not occur. The acceleration moves around so as to be always perpendicular to the velocity, which retains the same magnitude.

Analogy: A stone, whirled around on a string in a circular path at constant speed, has a constant acceleration toward the center.



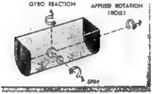
GYRO REACTION

A torque applied to a spinning gyro makes it precess at a constant rate. By Newton's third law of motion ("action and reaction are equal and opposite"), the gyro resists the precession by an equal and opposite torque. This opposing torque is known as the gyro reaction, and is the torque exerted by the gyro on its bearings and support. Suppose that a gyro is rigidly installed on a moving body (such as a missile or ship), and that its spin axis is horizontal. If the body changes its direction while the gyro is spinning at high speed, the direction of the spin axis will change by the same amount. This change in direction of the spin axis is sometimes called "forced precession". We prefer to call it applied rotation, reserving the term "precession" for that constant velocity brought about by a constant torque. Just as a torque caused precession, so does an applied rotation cause a torque. An applied rotation calls forth a reaction torque by the gyro against its bearings and supports — a gyro reaction, in fact, equal to $I\omega\dot{A}$, where I is the moment of inertia, ω the spin velocity, and $\dot{A}$ the applied rotation velocity. This gyro reaction is equal and opposite to the torque that would be required to produce a precession equal to the applied rotation.

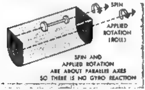
If the gimbal supporting the gyro is spring-connected to the housing, the gyro reaction can be measured by the stretch of the spring. (This stretch must be very small, so that spin and applied rotation are still about mutually perpendicular axes.) From the amount of stretch we can compute the rate of applied rotation, $\dot{A}$. This is the principle of the rate gyro, described in the next section. We can now devise a new set of axes.

EXAMPLE OF GYRO REACTION

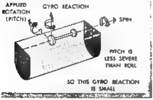
If a rotating wheel in the engines of a ship is mounted with its shaft athwartships, when the ship rolls the shaft exerts a gyro reaction on its bearings about a vertical axis, wearing to the bearings.

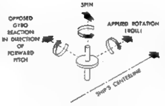


To avoid this the shafts are aligned fore-and-aft. Then the spin and applied rotation axes are parallel and there is no gyro reaction due to roll.

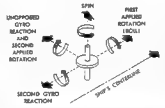


There is a gyro reaction due to pitch.

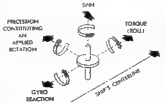




UNSUCCESSFUL SHIP STABILIZER. Wheel gimbal clamped so that it cannot pitch with respect to the ship. Merely slightly modifies ship's own pitch.



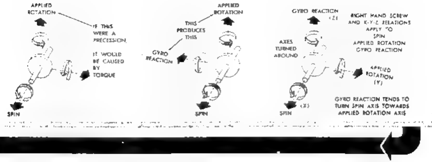
SUCCESSFUL SHIP STABILIZER. Gimbal free, so wheel pitches forward with respect to ship. This constitutes a second applied rotation which generates a second gyro reaction opposing roll.



Same stabilizer considered from spin-torque-precession viewpoint. Waves supply a (roll) torque, gyro precesses forward. Precession is the applied rotation which generates the gyro reaction opposing the original torque, i.e. roll.

SPIN-APPLIED ROTATION-GYRO REACTION

rule of axes



We have these two viewpoints because certain extreme cases can be considered from only one of them. Take the original case of a gyro with its spin axis horizontal; a weight hung on the spin axis. There is no rotation in the direction of torque. Instead, there is steady precession about a vertical axis. This case must be considered from the spin - torque - precession viewpoint. Or, take the case of a rate gyro. A steady rotation is applied. The gyro tries to rotate about an axis perpendicular to the spin and applied rotation axes, but no rotation occurs other than that permitted by the very slight stretching of a spring. This case must be considered from the spin - applied rotation - gyro reaction viewpoint. But, if there is an applied rotation, and the gyro reaction is not resisted — as in the successful stabilizer — we have three actual modes of rotation present at the same time. Such cases can be considered from either viewpoint. Note that if the first applied rotation persists, the produced rotation (or precession) does not last long. It stops as soon as the spin axis has lined up with the applied rotation (or torque) axis.

This method of stabilizing a ship was later superseded by other devices, but it is instructive as illustrating gyro principles. Stabilization is very much in use today - not ship stabilization, which has largely been discontinued, but stabilization of gun platforms, telescopes, radars, etc. The methods used generally involve servo mechanisms. One very important method will be discussed under "Functions of Gyro Devices".

CLASSROOM GYRO WITH ATTACHED WEIGHT, SHOWN PRECESSING

SUMMARY

A gyro is a wheel spinning at high velocity, thereby possessing properties useful in ordnance and other areas. When a torque is applied to a gyro about an axis perpendicular to spin, it precesses about an axis perpendicular to both of these; the spin axis pursues the torque axis. When a rotation is applied to a gyro about an axis perpendicular to spin, it exerts a torque — gyro reaction — on its bearings and supports about an axis perpendicular to the other axes; the spin axis tries to pursue the applied rotation axis.

PROBLEMS

1. State what happens, and why, when the following operations are performed. (It is assumed that gimbal A is always rotated clockwise, looking from above.)

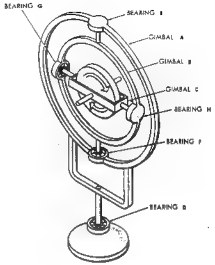
(1) Gyro spinning
Bearings G and H free.
Bearings E and F clamped.
Gimbal A rotated about bearing D.

(2) Gyro not spinning.
All bearings free.
Gimbal A rotated slowly about bearing D.

(3) Gyro spinning.
All bearings free.
Gimbal A rotated slowly about bearing D.

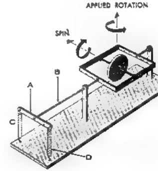
(4) Gyro spinning.
All bearings free.
Gimbal A rotated rapidly about bearing D.

(5) Gyro spinning.
Bearings E and F free.
Bearings G and H clamped.
Gimbal A rotated slowly about bearing D.

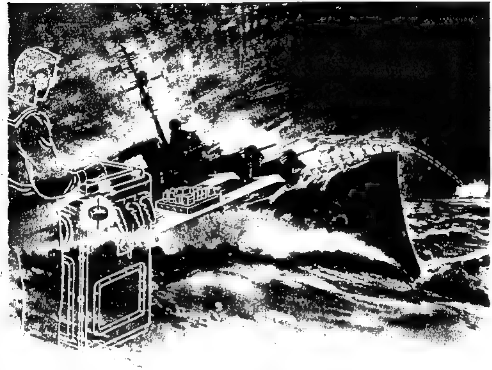


2. A 1-pound gyro (neglect weight of gimbals), spinning at 4 revs/sec., has an 8-ounce weight hung on its (horizontal) spin axis, 3 inches from the center. Wheel is one foot in diameter. How long (to the nearest second) does it take to precess once around its vertical axis? If we double the rate of spin, how long does it take?

3. The wheel of a rate gyro is a uniform flat disk, 2 inches in diameter and weighing 0.2 pound. It spins at 6000 rpm. Its supporting gimbals are connected by arm A to a pair of springs, 3 inches on either side of axis B. The vessel on which the gyro is mounted makes a turn at 10°/sec. to the left. This applied rotation creates a gyro reaction: arm A is deflected, elongating one spring, and compressing the other (1/8 inch for 1/10 lb. of force on the spring). Which spring elongates, and by how much? Through what angle is arm A deflected? (The answers to these questions need only be approximate.)



FUNCTIONS OF GYRO DEVICES



Cross level and level, measured by the stable element, are transmitted through electronic circuits to stabilize the guns.

There are two fundamental ways of mounting a gyro. A: to constrain it by a spring or a torque motor; B: to mount it as a free gyro, with freedom of rotation in all directions.

CONSTRAINED GYRO

A constrained gyro can be used in two basic ways: 1) Rotation can be applied and gyro reaction measured. This is the principle of the "rate gyro". 2) Torque can be applied and precession be the output. This is the principle of the "integrating gyro". If angle of precession is measured, this gives us direct integration. If the applied torque is adjusted to make the precession track a moving object, and the torque is then measured; this gives us inverse integration, i.e., rate measurement.

FREE GYRO

A free gyro can be used to establish a fixed reference, usually vertical or horizontal. The use of this principle in two important fire-control devices are discussed: 1) The stable element, used in measuring roll and pitch, or cross-level and level, and 2) the gyro compass, used in measuring yaw and own ship's course.

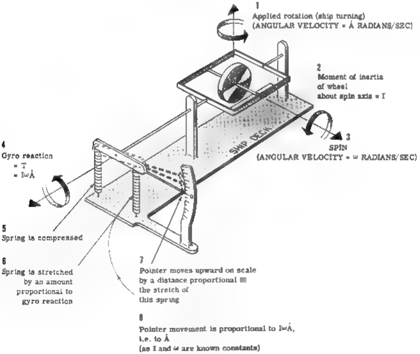
CONSTRAINED

A gyro with one of its modes of rotation constrained by a spring, or torque motor, may be used in two ways. One makes use of spin-applied rotation-gyro reaction. Rotation is applied to the gyro; the resulting gyro reaction stretches one of the springs and compresses the other, or the reaction is resisted by the torque motor. The measured gyro reaction tells us the rate of rotation. This device is called a rate gyro.

The other use of a constrained gyro is to apply the torque, and obtain precession. The gyro is then an integrator, because the angle precessed

APPLIED ROTATION . .

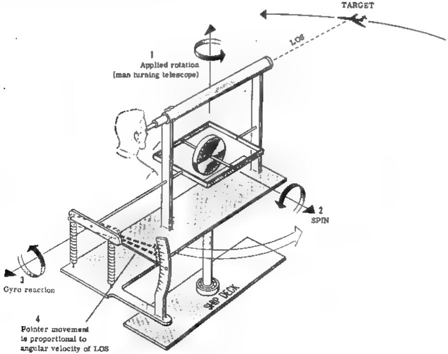
Below is shown the principle of a rate gyro as used to measure the rate of turn of a ship on which it is mounted. The ship supplies the applied rotation; springs supply the constraint, and measure the gyro reaction.



through is the time-integral of the input torque. An integrator can be used either: 1) to observe the angle precessed through, and thereby derive the time-integral of the torque, or 2) to adjust the torque so that the gyro follows a moving line-of-sight; the torque is then observed, and provides the angular rate of the line-of-sight. Note that in the last example we end by differentiating line-of-sight position. Yet, the gyro is still an integrator. Torque is still the input (as well as being measured), and rotation is still the output, but the output is compared with the motion of an object.

(gyro reaction measured — rate gyro)

Below is shown the principle of a rate gyro as used to measure the angular velocity of a line-of-sight. A telescope, trained on the target, supplies the applied rotation; springs supply the constraint, and measure the gyro reaction.



APPLIED TORQUE . . . . INTEGRATING GYRO

DIRECT INTEGRATION

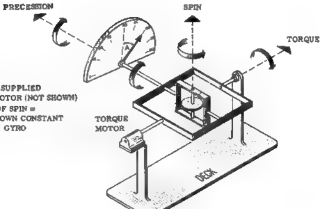
A torque, proportional to some quantity whose time integral is desired, is applied to a gyro, causing it to precess. Since rate of precession is proportional to torque, the angle precessed through is proportional to the time integral of torque.

$$\text{Torque} = T = I\omega \frac{dA}{dt}$$

$$\dot{A} = \frac{T}{I\omega}$$

$$A = \frac{1}{I\omega} \int T dt$$

(since I and ω are constant)

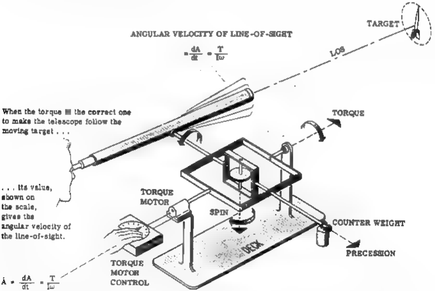


When the input is torque, and the output is precession, the gyro is called an integrating gyro. It can be used for direct integration, or for rate measurement.

RATE MEASUREMENT *(torque measured)*

An integrating gyro can be made to measure angular velocity, not by direct differentiation (as with a rate gyro), but by an indirect method. Suppose we wish to measure the angular velocity of the line-of-sight to a moving target. A telescope is attached to a gyro which is oriented so that, when it precesses, the telescope follows the same path as the line-of-sight. A torque is then applied to the gyro; this torque is varied until the target stays on the cross hairs of the telescope. The magnitude of the torque then gives the rate of precession: $\dot{A} = T/I\omega$; I and ω are known constants.

An integrating gyro used in this manner is sometimes called a precession rate output gyro.



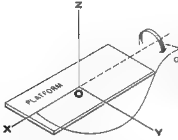
In the chapter on Speed Measurements we discussed various devices called integrators because their output is the time integral of their input. For instance, in the familiar mechanical integrator, the input is the movement of a ball carriage, while the output is the rotation of a cylinder. It was pointed out that an integrator can be used to measure rates by finding out what movement of the ball carriage will cause the cylinder rotation to follow a moving object. This is an indirect method of using an integrator to differentiate. Here, in gyros, we have a similar situation. The input is torque; the output is precession. The output is the time integral of the input. We find out what input will make the output follow a moving object. Again, this is an indirect method of using an integrator to differentiate. There is a difference in the two cases. The ball-and-roller integrator is irreversible; you cannot make the ball carriage move by turning the cylinder. So, it can measure rates only by an indirect method. But a constrained gyro is reversible; you can apply a torque and obtain precession (indirect method), or you can give an applied rotation and obtain a gyro reaction (direct method).

FREE

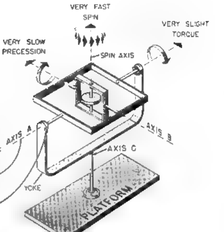
A free gyro differs from a constrained gyro in that the free gyro is free to rotate in all directions. Its principal use is to establish a fixed direction reference. Applications of this are

GYRO AS FIXED

Suppose that a big, heavy, fast spinning gyro is mounted so it has universal motion, and that the base rests on a platform capable of angular movement about either of the three axes, OX, OY, and OZ. Axes OX and OY are in the platform; axis OZ is perpendicular to the platform.



If the platform rotates about OX, a very slight torque will be exerted on gyro axis A, caused by the friction of its bearings.



This will result in a very slow precession of the gyro about axis B, the rate of precession being given by equation:

$$\dot{A} = T/I\omega$$

If the bearings are nearly frictionless, and the wheel is big, heavy, and spinning fast enough — that is, if T is small enough and I and ω big enough — then $\dot{A}$ can practically be zero. This precession is imperceptible — yet it is present, and with it its most important property: that of preventing all other motion of the gyro, except spin. (In the section on Basic Gyro, a mathematical derivation of the law of precession was given. It showed that the angular acceleration due to torque was fully accounted for by the velocity of precession.) Thus, when the platform rotates about OX, axis B will preserve its horizontal position, and the spin axis its vertical position.

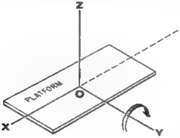
Thus, the gyro maintains its position in space throughout both rotations. However, the innermost gimbal would not maintain its position if the platform rotated about OZ. That is because the axis of the torque produced at the axis C bearing is parallel to the spin axis, so the gyro would not precess. So the torque, though slight, would cause the whole system of gimbals and gyro to turn around with the base. To achieve stability about OC, a second gyro must be used, mounted with its spin axis horizontal. It could be attached to the innermost gimbal.

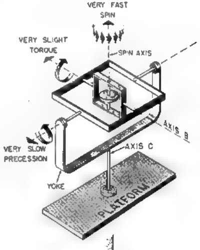
In 1852, Leon Foucault, of Paris, made use of this property of gyros to show the rotation of the earth. But it is the earth that is moving, and the gyro that is at rest (except for its spinning and minute precession). For simplicity, the gyro is shown at the equator.

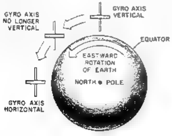
the stable element for vertical reference, and gyro compass for horizontal reference. First, let us discuss the property which enables a gyro to serve as a fixed direction reference.

DIRECTION REFERENCE

Suppose the platform rotates about OY instead of OX. The gyro will experience a very slight torque due to the slight friction between axis B and its bearings. This will cause an imperceptible precession about axis A. Axis A tilts with the platform, but axis B does not turn in space, so the spin axis remains vertical.







This property—apparent "rigidity"—can be made use of in two principal ways. One is to measure the rotation of the platform; the other is to establish a second, stable platform. (In both operations it is important that only the slightest load, if any, should be put on the innermost gimbal; otherwise, a perceptible torque will be on it, causing the gyro to precess excessively.)

Stated in a more general way: a free gyro (with certain artificial aids) can be used to establish a FIXED REFERENCE, as will be discussed in more detail in the following pages.

ESTABLISHMENT OF A FIXED REFERENCE

In any weapon control operation, fixed reference axes are required, such that rotation about them can be measured and corrected for. A gun platform needs to be stabilized in roll, pitch, and yaw. A missile needs to have any rotation away from, or about, its course measured and corrected for.

In operations lasting a short time, this can be achieved by free gyros which display their so-called "rigidity", and maintain a constant direction of their spin axes. Follow-up circuits will detect deviations from this direction on the part of the platform or missile framework, and supply the needed correction. However, in operations lasting a relatively long time, various slight forces and disturbances acting on the gyro will gradually cause it to depart from its original direction. We cannot trust an unassisted free gyro; we must establish an artificial standard or reference.

In general, two non-collinear axes will suffice to measure any rotation. (They imply a third axis, perpendicular to both.) In other words, two gyros with non-collinear spin axes can solve any stabilization problem, provided that their spin axes can be stabilized in fixed directions. (One gyro can sense both roll and pitch, and another gyro can sense yaw.)

It [redacted] impractical to choose a fixed "space" direction for either of the spin axes—such as pointing it at a fixed star. [redacted] would be possible to stabilize the spin axis in such a direction only by some artificial contrivance such as a photoelectric cell. Besides, space reference may not be convenient [redacted] weapon control, when missile or platform and target are basically earth-referenced.

We want [redacted] find two axes, fixed with relation to the earth, that natural forces will bring the spin axis back to when it deviates from these axes. The most obvious force is gravity, which can be made to establish a fixed reference; that is, to stabilize a gyro with a vertical spin axis. This [redacted] the principle of the STABLE ELEMENT, as discussed later. This suggests making a horizontal reference. The rotation of the earth, combined with gravity, can be used to stabilize a gyro with a horizontal spin axis pointing north. This [redacted] the principle of the GYRO COMPASS, as discussed later on.

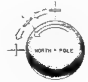
ESTABLISHMENT OF A VERTICAL REFERENCE

GENERAL

Assume that a set of gimbals is mounted on the deck of a ship, but [redacted] not given any special orientation with respect to the ship. In fact, [redacted] is not even given a constant orientation, because the whole system is steadily rotated about a vertical axis. Its sole object is to provide a constant vertical reference. It is convenient to make this vertical with respect to the earth, so that gravity can be used [redacted] a reference, and so that [redacted] can be used [redacted] conjunction with quantities which involve an earth-vertical plane, such as roll, pitch, level, and cross-level. To achieve this, an erector system is used.

ESTABLISHMENT OF A VERTICAL REFERENCE

LATITUDE WEIGHT



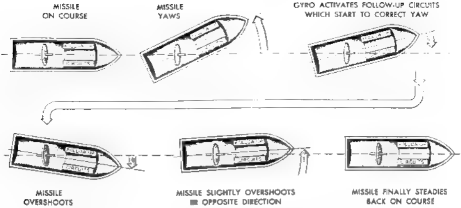
GYRO AT EQUATOR

It is not desired that a free gyro strictly maintain its direction in space, but that its spin axis should always point to the center of the earth. To do this, it must be made to precess. A latitude weight is used to correct loss of verticality due to the earth's rotation.

The latitude weight gets its rather misleading name from the fact that the desired rate of precession (and, therefore, the torque exerted by the weight) is different at different latitudes (maximum at the equator; zero at the poles). It is not a correction for latitude; [redacted] is a correction for rotation of the earth.

Since the desired precession is about the axis of the earth, [redacted] must always be in the same direction (relative to the earth). That is to say, the torque must always be [redacted] the same direction. Therefore, the latitude weight must not be hung on a gimbal, because the gimbals and wheel are all rotating at about 20 revolutions per minute (for operation of the mercury control system).

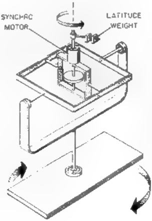
GYRO AT NORTH POLE

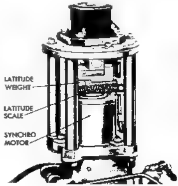


First, it is important that the gyro should not exactly maintain its direction in space, for if it did, its spin axis would not continue ■ point toward the center of the earth.

Instead, we wish the gyro ■ behave like this: To achieve this, we hang a small latitude weight on a shaft mounted at the top of one of the gimbals, (as shown below) to produce an "applied torque" to give it a precession such that it will be coincident with the extended radius of the earth. Additional precession ■ generated by a mercury control system to restore lost verticality caused by local disturbances. To operate the system, a motor rotates the gimbals and gyro steadily about a vertical axis at about 20 revolutions per minute.

A small synchro motor is mounted on the top of the vertical gimbal; its rotor rotates at the same speed ■ the structure, but in the opposite direction. Thus, anything attached to the rotor is at rest, relative to the earth. The rotor supports a small arm, which supports the weight. The figures at right show the latitude weight: 1) in principle. 2) in actuality. The latitude weight consists of two knurled nuts on a threaded rod. The scale is for adjusting the weight's position. At low latitudes, the nuts are moved further out on the rod than at high latitudes, so as to produce a higher torque and faster precession.

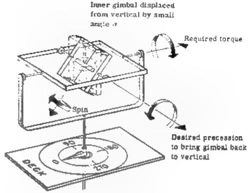




ESTABLISHMENT OF A VERTICAL

preliminary analysis

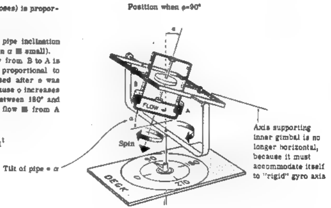
The mercury control is a portion of the erector system used to restore the gyro to vertical when it departs from vertical because of some local disturbance, such as bearing friction. **Suppose the inner gimbal has been displaced by an angle α from vertical, as shown at the right. We must apply a torque on the gyro that will cause it to precess back to vertical. When we have succeeded, α will decrease.**



Rate of flow (for practical purposes) is proportional to tilt of pipe.

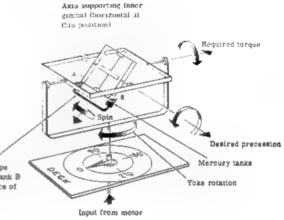
At intermediate positions, the pipe inclination [illegible] the horizontal is $\alpha \sin \phi$ (when α [illegible] small). It follows that the rate of flow from B to A is proportional to $\sin \phi$; that is, proportional to $\sin k_1 t$ (where t is time elapsed after ϕ was zero, and k_1 is a constant), because ϕ increases at a uniform rate. When ϕ is between 180° and 360°, $\sin \phi$ is negative, and the flow [illegible] from A to B.

$$\text{Rate of flow} = k_2 \alpha \sin \phi$$
$$= k_2 \alpha \sin k_1 t$$

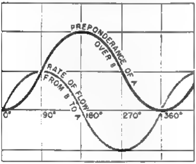


Mercury flowing from tank B to tank A.

Consider the effect of attaching to the inner gimbal two tanks (A and B) partly filled with mercury, and connected by a pipe; also rotating the whole gyro-gimbal structure horizontally at about 20 r.p.m., in the same direction as spin. Let ϕ be the horizontal angle through which the structure has been turned from the position shown [redacted] the illustration at the right.



If tanks start having equal weight, the rate of flow and the preponderance of mercury in tank A are as shown below:



Preponderance of mercury in tank A

$$= \int_0^t (\text{rate of flow})\, dt$$

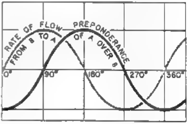
$$= k_2\, \alpha \int_0^t \sin k_1 t\, dt$$

(if we neglect the slow change in α)

$$= (k_2/k_1)\, \alpha\, (1 - \cos k_1 t)$$

This would make A always the heavier.

If, instead, we start with B the heavier by a suitable amount, we can obtain the symmetrical arrangement shown below:



Preponderance of mercury in tank A

$$= (k_2/k_1)\, \alpha\, (1 - \cos k_1 t)$$

$-$ preponderance of B when $t = 0$

$$= (k_2/k_1)\, \alpha\, (1 - \cos k_1 t) - (k_2/k_1)\, \alpha$$

$$= -(k_2/k_1)\, \alpha \cos k_1 t$$

Thus, for values of $k_1 t$—i.e., values of ϕ—between 270° and 0° and between 0° and 90°, the preponderance of A is negative; that is [redacted] say, B is the heavier. For values of ϕ between 90° and 180°, and between 180° and 270°, A is the heavier.

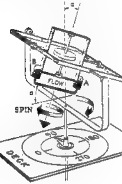
ESTABLISHMENT OF VERTICAL REFERENCE —MERCURY CONTROL

completion of cycle

WHEN $\phi = 90°$:

Tanks are now of equal weight. Thus, torque is zero, and there is no precession. Desirable, because in this position it could not diminish α; inner gyro is on "dead center". From this position through values of ϕ through 180° to 270°, A will be the heavier.

POSITION WHEN $\phi = 90°$

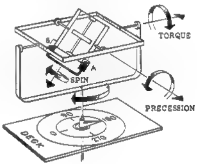


Torque is proportional to preponderance of mercury in tank A, viz: $-(k_2/k_1)\ \alpha \cos \phi$. Thus, torque is proportional to α. Thus, rate of precession ($A = T/I\omega$) is proportional to α. As verticality is approached, and α decreases, torque and rate of precession become negligible, so there is no overshoot.

WHEN $\phi = 180°$:

The pipe is level again (angle $= \alpha \sin 180° = 0$), and flow has ceased. But A has its maximum preponderance over B. Torque is a maximum, as B was at 0°, only it has the reverse direction with respect to the equipment, but has the same direction in space. The same is also true of precession. Now, as we move toward 270°, A rises above B, and flow reverses its direction.

POSITION WHEN $\phi = 180°$

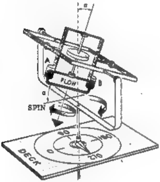


Rotation of whole structure is about an axis perpendicular to deck. This produces a slight torque (due to friction of bearings) tending to align spin axis so as to be perpendicular to deck. This torque is negligible compared with torque established by mercury tanks which tends to align spin axis with extended radius of earth.

WHEN $\phi = 270°$:

Flow from A to B is maximum, but the tanks have equal weight, so the torque is again zero. Now B begins to get heavier, and continues to be heavier through 0°, and on to 90°.

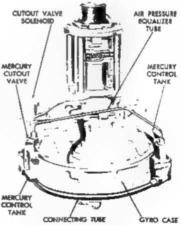
POSITION WHEN $\phi = 270°$



The cycle repeats itself until the inmost gimbal is vertical. After that, the horizontal rotation of the structure no longer affects the tanks, and the flow of mercury stops.

We have considered flow as caused entirely by tilt. When the pipe is horizontal (at 0° and 180°), tanks contain unequal weights of mercury, but the difference in mercury levels is negligible.

At the right is shown a vertical reference equipment, emphasizing the mercury control. When the ship experiences accelerations or rapid turns, that might cause an unwanted flow of mercury, the operation of the control can be stopped automatically by means of the mercury cutout valve.



MEASUREMENT OF DECK INCLINATION

GENERAL

A vertical reference, like the one we discussed, can be used to measure the inclination of a ship's deck, from moment to moment. There are many ways of doing this. For instance, a beam of light could be shone from the vertical reference on to a mirror on the deck, and reflected onto a scale. Or, the vertical reference could be observed through a graduated glass dome on the deck. Or, the vertical reference could be fitted into a universal joint attached to the deck; then the deck's movements could be picked up by a system of gears, and thus analyzed into their two components (roll and pitch, cross-level and level, or other components into which we wanted to resolve the movements).

A method much used in fire-control equipment is to make the vertical reference bring into position a set of rings, by an electrical follow-up system. These rings are physically similar to the gimbals we have been discussing — those used to set up the vertical reference. This is a misleading coincidence. It must be emphasized that the use of gimbals at this point is not chosen for any gyroscopic reason. They are just a convenient way of using the vertical reference established by the gyro gimbals. The follow-up gimbals support no gyro. Their structure is not rotated, but given a fixed orientation with respect to the ship or line of sight. They are not in physical contact with the gyro gimbals, or any part of the vertical reference, but support follow-up coils receiving signals from the vertical reference.

An electromagnet is mounted on the top of the innermost gyro gimbal. This induces currents in follow-up coils; these currents are used to position the follow-up gimbals. Attached to the innermost follow-up gimbal is an umbrella made of non-conducting material. Mounted on the umbrella are the two follow-up coils, one for each gimbal motion; their windings are at right angles to each other. Each follow-up coil is connected to an a-c motor, through a control circuit consisting of an amplifier, a rectifier circuit, and an anti-hunt unit.

The complete equipment is called a STABLE ELEMENT. It includes the vertical reference (gyro and gyro gimbals, and the erector system, contained in a case), follow-up gimbals, and the elements of the follow-up circuits, the motors, and the gear trains. The follow-up gimbals can be aligned with any reference axis, according to the position of the yoke (outermost support).

The figure at the right shows the general case in which the yoke deck axis is aligned along an unspecified line in the deck. Two rotations are measured: 1) about this line, and 2) in a plane through this line perpendicular to the deck.

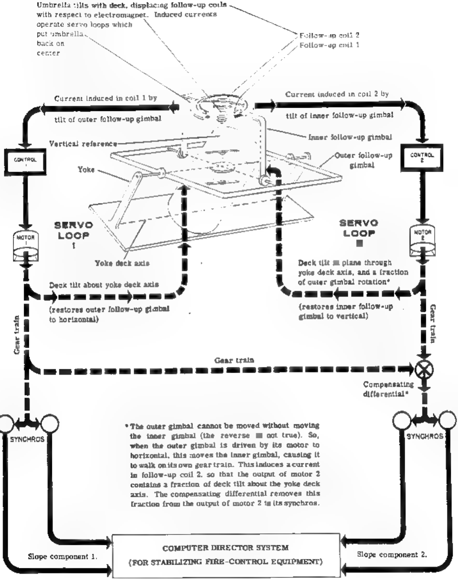
On the following page, three special cases will be demonstrated; viz. the measurement of:

1) Roll Zo, and Pitch Elo.

2) Cross Level Zd, and Level El.

3) Level El', and Cross-Level Z'.

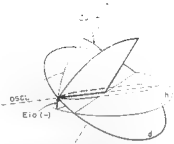
The quantities most often measured are Zd and El. Nevertheless, we shall begin by discussing the measurement of roll and pitch, because the fixed orientation of the yoke (along the ship's centerline) make it the easiest of the three setups to understand. (El' and Z' are measured when operating against targets on the horizon.)


Umbrella tilts with deck, displacing follow-up coils with respect to electromagnet. Induced currents operate servo loops which put umbrella back on center
Follow-up coil 2
Follow-up coil 1
Current induced in coil 1 by tilt of outer follow-up gimbal
Current induced in coil 2 by tilt of inner follow-up gimbal
Inner follow-up gimbal
Vertical reference
Outer follow-up gimbal
CONTROL 1
CONTROL 2
Yoke
SERVO LOOP 1
SERVO LOOP 2
MOTOR 1
MOTOR 2
Yoke deck axis
Deck tilt about yoke deck axis
(restores outer follow-up gimbal to horizontal)
Deck tilt in plane through yoke deck axis, and a fraction of outer gimbal rotation*
(restores inner follow-up gimbal to vertical)
Gear train
Gear train
Gear train
Compensating differential*
SYNCHROS
SYNCHROS
* The outer gimbal cannot be moved without moving the inner gimbal (the reverse is not true). So, when the outer gimbal is driven by its motor to horizontal, this moves the inner gimbal, causing it to walk on its own gear train. This induces a current in follow-up coil 2, so that the output of motor 2 contains a fraction of deck tilt about the yoke deck axis. The compensating differential removes this fraction from the output of motor 2 to its synchros.
COMPUTER DIRECTOR SYSTEM
(FOR STABILIZING FIRE-CONTROL EQUIPMENT)
Slope component 1.
Slope component 2.

MEASUREMENT OF ROLL AND PITCH

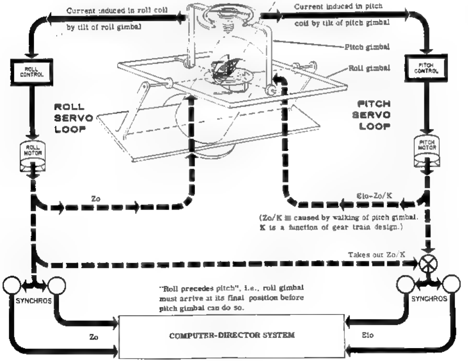
If the yoke is aligned with own ship centerline, the gimbals will measure the roll and pitch.

Roll (Zo): Angle between two planes. One plane is vertical through own ship centerline. The other plane, perpendicular to the deck, is through own ship centerline. The angle is measured about own ship centerline.



Pitch (Eio): Angle between the horizontal plane and the deck plane. Angle measured in vertical plane through own ship centerline.

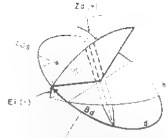
(The arrows in the above figure represent the directions of roll and pitch themselves, i.e., the opposite of the corrections performed below.)



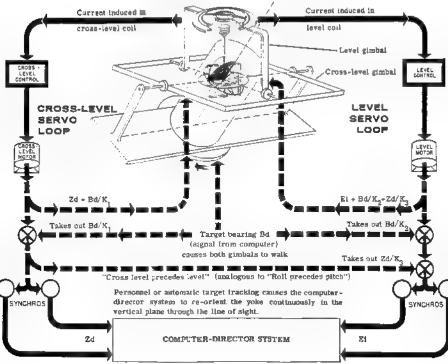
MEASUREMENT OF CROSS LEVEL Zd AND LEVEL Ei

If the yoke is aligned with a horizontal projection of the line of sight, the gimbals will measure cross level Zd and level Ei.

Cross level (Zd): Angle between two planes. One plane is vertical through the line-of-sight. The other plane, perpendicular to the deck, is through the intersection of the deck plane with the vertical plane through the line-of-sight. The angle is measured about the axis which is the intersection of the deck plane with the vertical plane through the line-of-sight.

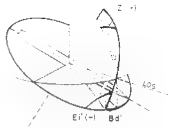


Level (Ei): Angle between the horizontal plane and the deck plane. The angle measured in the vertical plane through the line of sight.



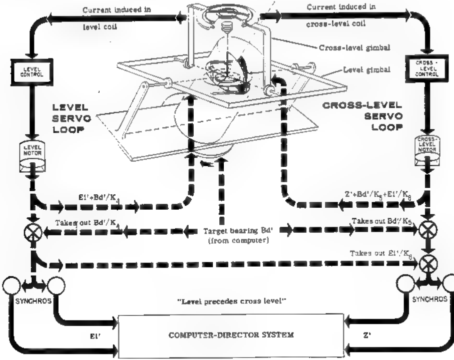
MEASUREMENT OF

If the yoke is aligned at right angles to the plane perpendicular to the deck through the line-of-sight, the gimbals will measure level and cross level, as defined below:

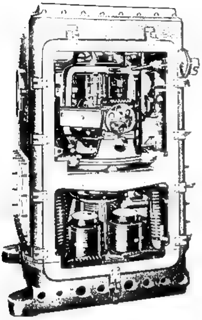


Level (El'): Angle between the deck plane and the horizontal plane. The angle is measured in plane through line-of-sight perpendicular to deck.

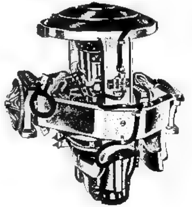
Cross level (Z'): Angle between two planes. One plane is through the line-of-sight, and perpendicular to the deck. The other plane is vertical, through the intersection of the horizontal plane with the plane through the line-of-sight perpendicular to the deck. The angle is measured about the axis which is the intersection of the horizontal plane with the vertical plane.



LEVEL Eí AND CROSS LEVEL Z′



typical
stable
element



ESTABLISHMENT OF A HORIZONTAL

need for precession

We have explained how to establish a vertical reference. Another reference is needed. If a gun were mounted on a ship that rolled and pitched and yawed, the stable element would take out roll and pitch, but could do nothing about yaw because its gyro spin axis is vertical, thus making it insensitive to rotation about a vertical axis. (This is explained under "Gyro as Fixed Direction Reference".) Or consider a missile aimed at a target. If forces acting on it caused it to roll, pitch, and yaw, a stable element mounted in it could eliminate only roll and pitch.

A system sensitive to yaw is required: i.e., a gyro with a horizontal spin axis. This would establish a horizontal reference, in the same manner that the stable element establishes a vertical reference.

But what horizontal reference?

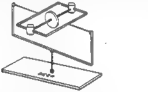
The target (stationary or moving) at which a missile is aimed, and that ship or site from which it is fired or launched, are both referenced to the earth. Therefore, it is desirable (and more practicable) that our horizontal reference also be an earth reference, such as north, rather than a "space" reference. Such an apparatus is called a gyro compass.

Suppose that a gyro, free to rotate about three axes, is mounted with its gimbals on a platform resting on the ground. Its spin axis is pointed at a fixed star (any star — not necessarily the North Star). As the earth rotates, the platform rotates with it. If the gyro were perfectly free -- that is to say, if the bearings were ABSOLUTELY frictionless — rotation would exert no torque on the gyro, which would continue to point at the star. Since there is a slight friction in the bearings, the rotation will exert a slight torque on the gyro about the axis of the earth.

The gyro will precess until its spin axis is parallel to the earth's axis, and "points at the North Star".

This is the simplest kind of gyro compass. However, it is impracticable, because:

This condition may be corrected by mercury tanks ("mercury ballistic"), but not used as they are in the stable element. There, they keep the spin axis vertical; here, they keep it horizontal. Here the tanks are mounted on the end of the spin axis. The gyro is not rotated, except by the rotation of the earth.



Before explaining how the mercury ballistic brings the axis back to the meridian, let us consider the final steady state arrived at. The spin axis is in the meridian. There is a slight preponderance of mercury in the south tank; the north end of the spin axis is slightly raised so as to equalize the levels of mercury in the tanks. No mercury flows between the tanks, so the torque exerted by the heavier southern tank is constant, and of such a value as to precess the spin axis at the right speed to counteract the earth's rotation, and keep the axis on the meridian.

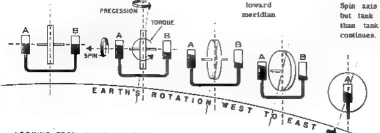
A gyro provided with a mercury ballistic does not merely hold the meridian; it seeks it. To take an extreme case, suppose that the spin axis is initially pointing east and west. (For simplicity, suppose that the gyro is at the equator. Holding the meridian when at the equator is no problem, but seeking it is, as much as at any latitude.) Because the gyro is freely mounted, it is independent of roll and pitch. (Stabilization in yaw is discussed later.)

Spin axis horizontal, tanks level.

If spin axis held its space direction, tank B would rise. Mercury would flow from B to A. Level in A would be higher. A would become heavier than B. Resulting torque would precess gyro so that A moved toward the south, and B toward the north. Now, consider what actually occurs.

Torque causes precession toward meridian

Spin axis now on meridian, but tank A is still heavier than tank B. So precession continues. We get "overshoot".



LOOKING FROM POINT ABOVE SOUTH POLE

DIRECTIONAL REFERENCE . . . GYRO COMPASS

1) The torque exerted by the once-in-24-hours rotation would be so small that the precession (seeking the North Star) would be excessively slow.

2) Any other rotation of the gyro platform—due to roll, pitch, and yaw of the ship—would be faster than earth rotation, and exert a greater torque, precessing the gyro axis toward some line not parallel to the earth's axis.

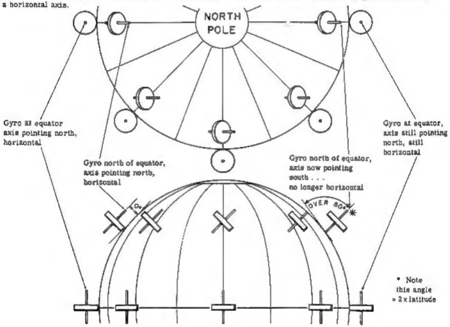
3) Even if it worked, this gyro compass would be undesirable because its spin axis would not be horizontal.

Gyro compasses used today differ in many ways, but they all have this in common: they are artificially made to precess — by an externally applied force — so as to pursue and then stay on the meridian, while maintaining a horizontal axis.

The important point is that we abandon the notion of trusting to the slow earth rotation to bring the gyro in line. We artificially correct the tendency of the gyro to preserve its original space orientation — and make it conform to the ever-changing space orientation of some earth orientation.

When the gyro is at the equator, and the axis is horizontal and aligned with the meridian, the rotation of the earth will not disturb this condition.

But, if it is at some other latitude—even though horizontal, and aligned with the meridian at a given instant—the rotation of the earth will change this condition. The north end of the axis will rise, and also point east of north.



Like any undamped correction device (e.g., servo mechanism), the mercury ballistic, if undamped, overshoots. Because tank A is now the more easterly tank, the earth's rotation causes it to rise (just as tank B rose when it was the more easterly tank). Tank A is still the heavier. So the torque is still in the same direction (with respect to the spin axis), and precession continues, with tank A still rising and mercury flowing from tank A to tank B.

So a cycle is set up, with the spin axis moving up and down as well as back and forth. If the gyro is undamped, the spin axis will describe a closed curve about the horizontal meridian. When damping is applied, the curve becomes a spiral ending in the desired steady state, with the spin axis in the meridian, the north tank being slightly raised above the south tank.

The same principle applies at other latitudes, and for small displacements from the meridian (as distinct from the extreme case of east-west orientation we considered).

ESTABLISHMENT OF A HORIZONTAL DIRECTIONAL REFERENCE—GYRO COMPASS

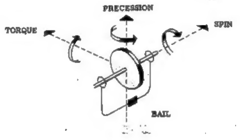
bail

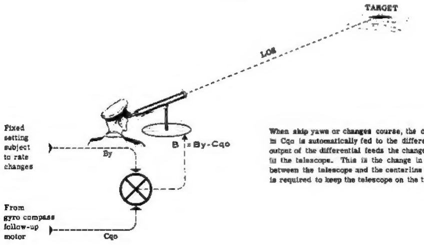
An alternative to the use of mercury tanks is the use of a bail; that is, a weight suspended below the gyro, as shown.

As the north-east end of the axis tilts up, the bail exerts a torque that is in the direction opposite to the torque exerted by the tanks. So, if we still want the gyro to precess so as to turn the north-east end westward, we must reverse its spin. For emphasis, we have exaggerated the upward tilt of the axis. We should still continue to think of the axes of spin, torque, and precession as orthogonal.

latitude weight

Still another device is the latitude weight discussed in connection with the stable element. The trouble with the latitude weight is that it always exerts the same torque, whereas the tanks and the bail exert a torque that diminishes and disappears at equilibrium, or (at latitudes other than the equator) sinks to the value required to keep on the meridian when it is found. The constant torque exerted by the latitude weight means a constant rate of precession. So, a gyro equipped with a latitude weight could either pursue the meridian, or hold the meridian, but not both.



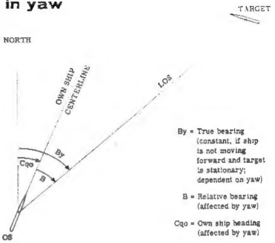


When ship yaws or changes course, the change in Cqo is automatically fed to the differential; output of the differential feeds the change in B to the telescope. This is the change in angle between the telescope and the centerline which is required to keep the telescope on the target.

stabilization in yaw

Suppose that it is desired to keep a telescope that is mounted on a ship aligned on a target. If the ship should yaw, the telescope will leave the target, unless measures are taken to bring it back again. A gyro compass in conjunction with follow-up circuits can be employed to correct for yaw, just as a stable element, together with its follow-up circuits, corrects for roll and for pitch, or for cross level and level.

For simplicity, it is presupposed that the ship is not moving forward, and the target is stationary. But they are moving, and therefore By changes. The change in By is computed by rate circuits, and fed continuously to the differential shown below at the left.



By = True bearing (constant, if ship is not moving forward and target is stationary; dependent on yaw)

B = Relative bearing (affected by yaw)

Cqo = Own ship heading (affected by yaw)

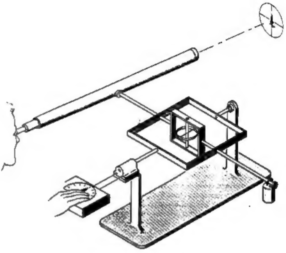
B = By - Cqo

SUMMARY OF FUNCTIONS OF GYRO DEVICES

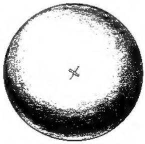
We have reviewed some of the principal uses of a gyro in fire control. Two forms of constrained gyro were studied: 1) the rate gyro, where applied rotation is the input, and gyro reaction the output, and 2) the integrating gyro, where torque is the input, and precession the output (although torque may also be the functional output leading to inverse integration, i.e. differentiation). Two uses of the free gyro were discussed: 1) the stable element, used in establishing a vertical reference, thereby measuring and stabilizing in roll and in pitch or cross level and level, and 2) the gyro compass, used in establishing a horizontal reference, thereby measuring and stabilizing in yaw.

PROBLEMS

1. In an integrating gyro, the wheel is in the form of a thin ring, 6 inches in diameter, and weighing 5 pounds. It spins at 7200 r.p.m. A torque is fed into it by a motor, causing the gyro to precess; this motion drives a telescope. When the telescope follows a moving target at a 5000-yard range, the torque dial reads 0.5 pound-foot. What is the approximate velocity component perpendicular to the target line of sight in ft./sec.?



2. A gyro compass with mercury ballistic is placed at the South Pole. Explain what it will do if:
(a) The spin axis is horizontal; both tanks hold the same amount of mercury.
(b) The axis is tilted slightly so as to equalize the levels in the tanks; one tank contains slightly more mercury than the other.
(c) The axis is tilted further (same direction).
Why is a gyro compass useless at either pole?



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